

*July* *Twenty*

# The Journal of the INSTITUTE OF METALS

*and*  
**METALLURGICAL ABSTRACTS**



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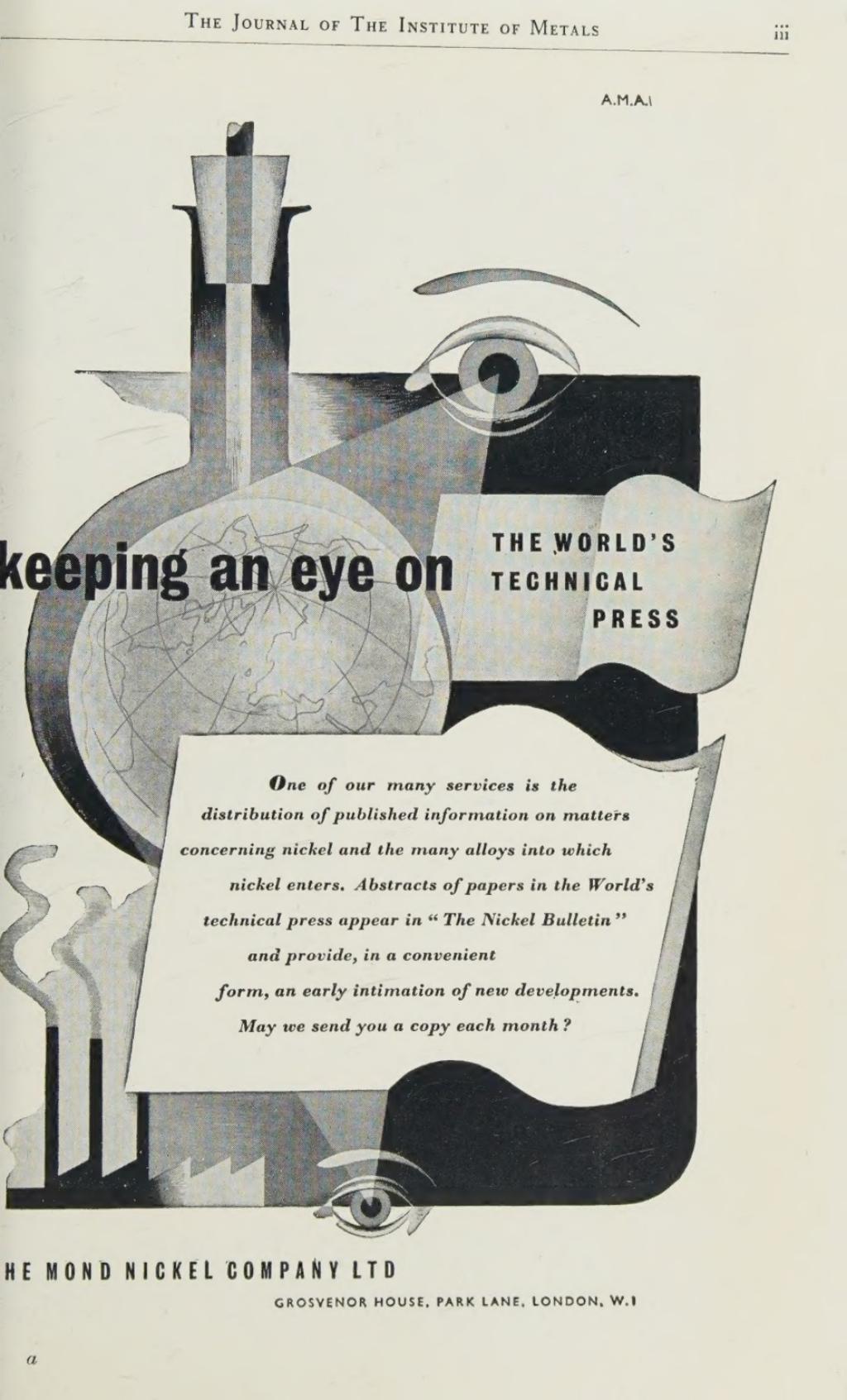


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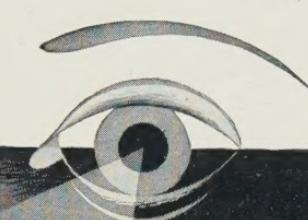


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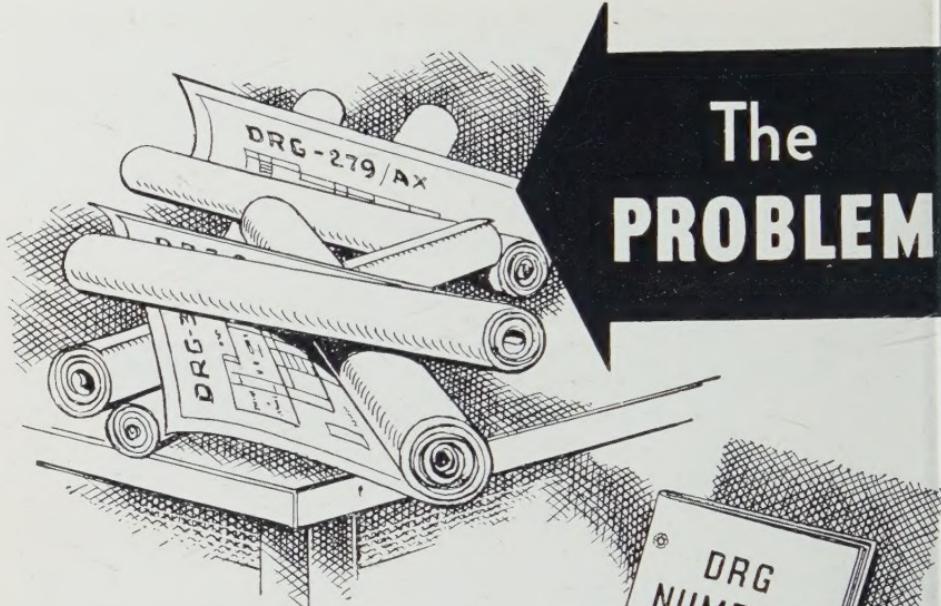


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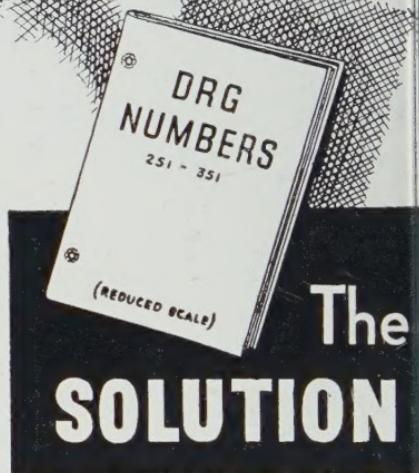
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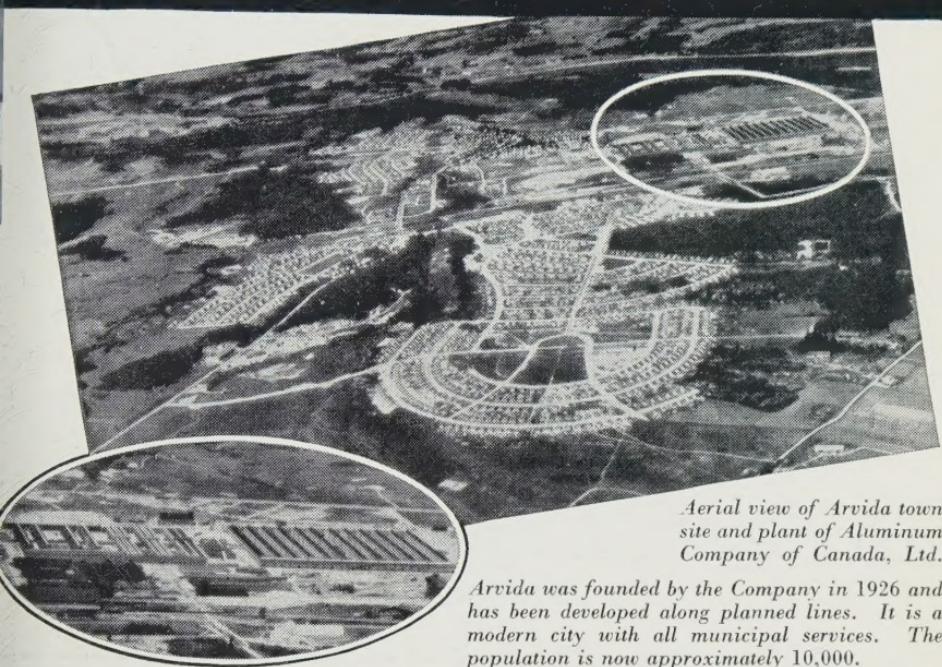


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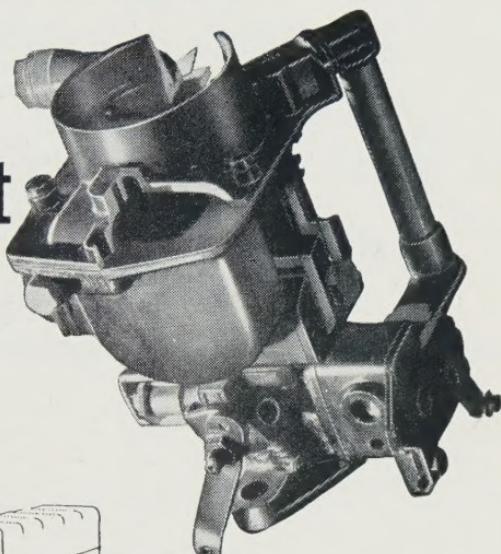
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**ACCURACY:** Castings can be made practically to finished dimensions and need little or no machining.

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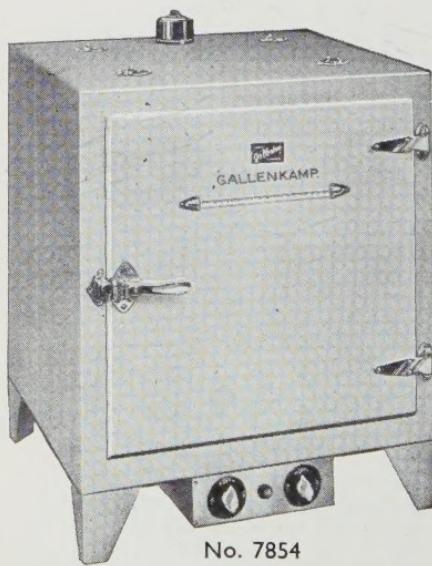


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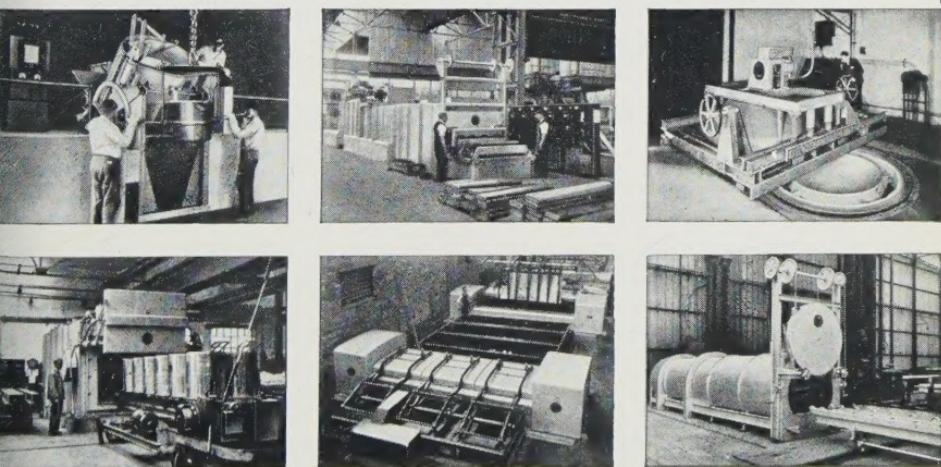
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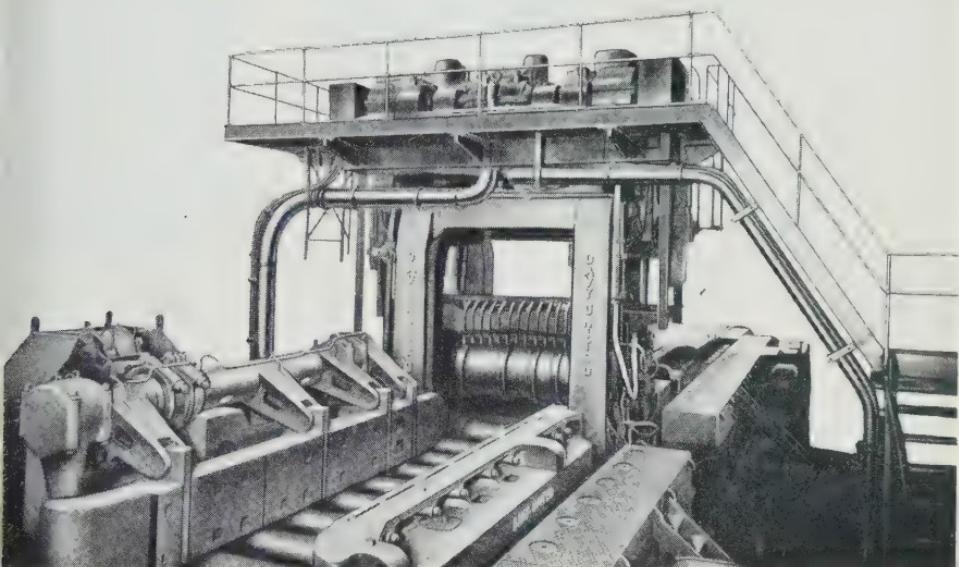
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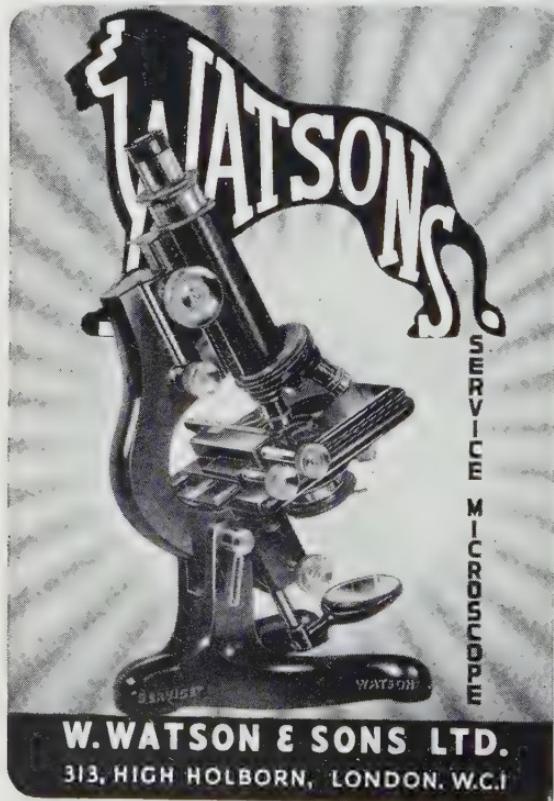
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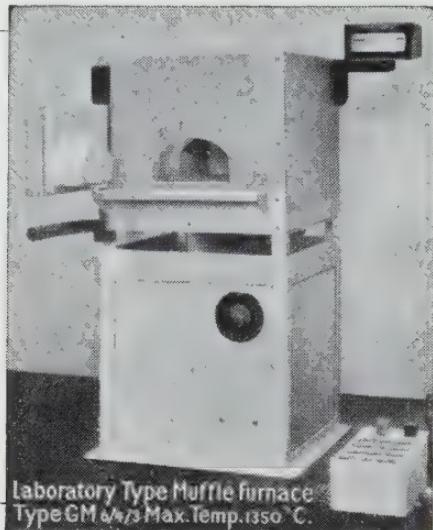


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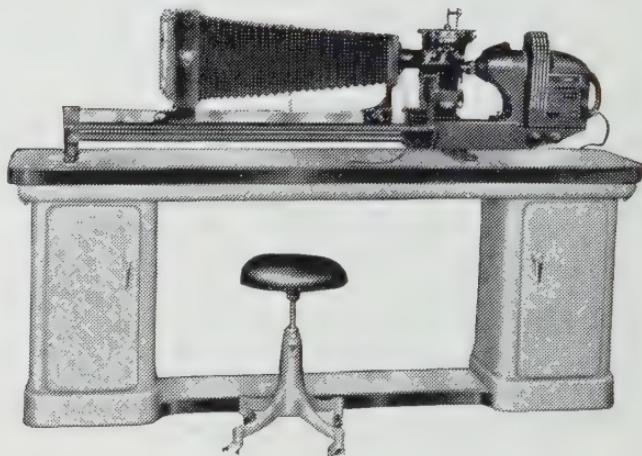
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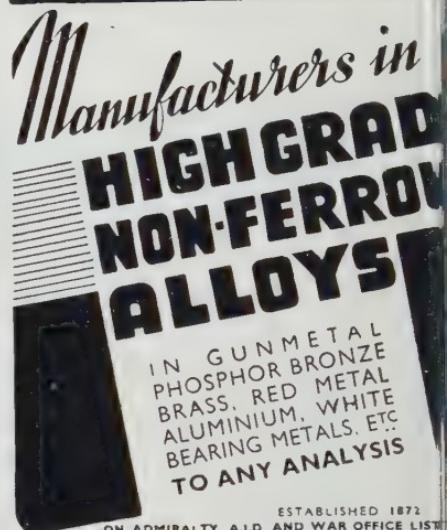
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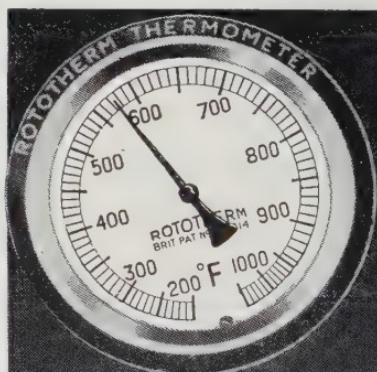
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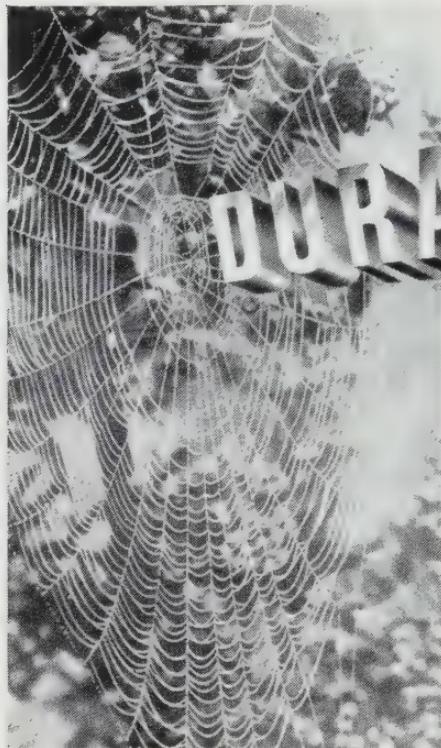
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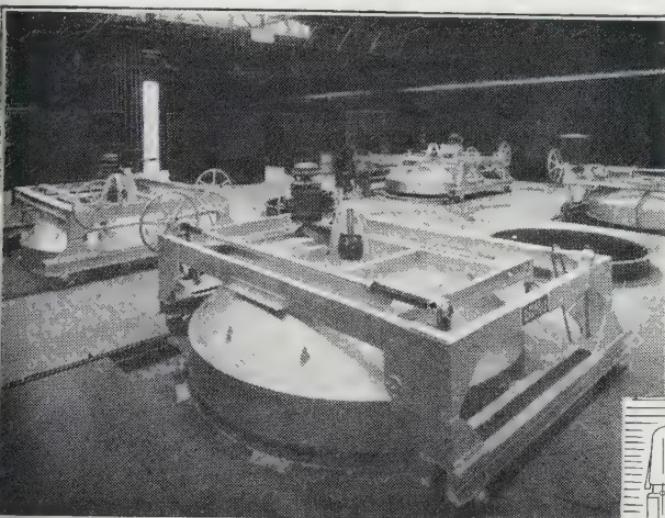
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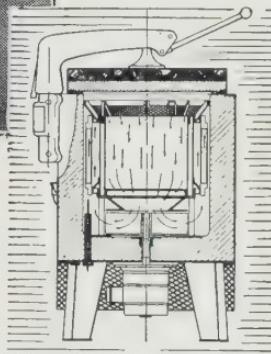
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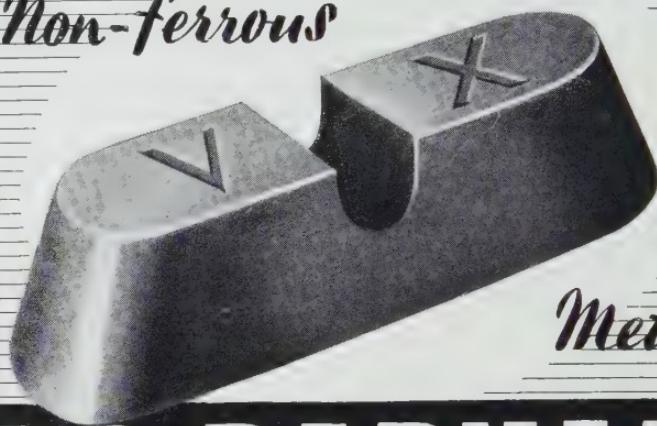
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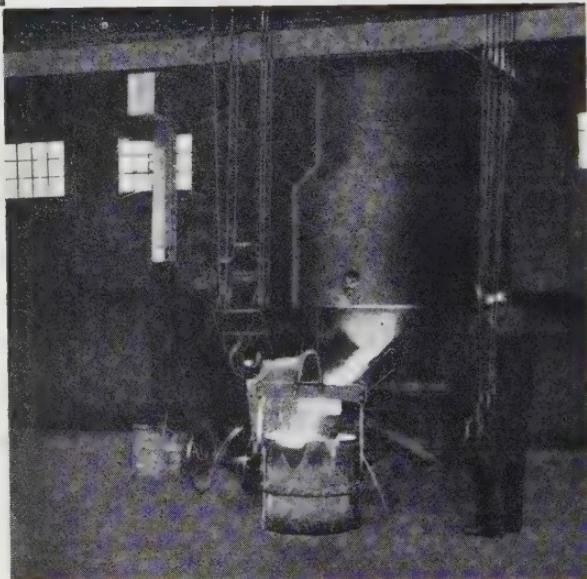
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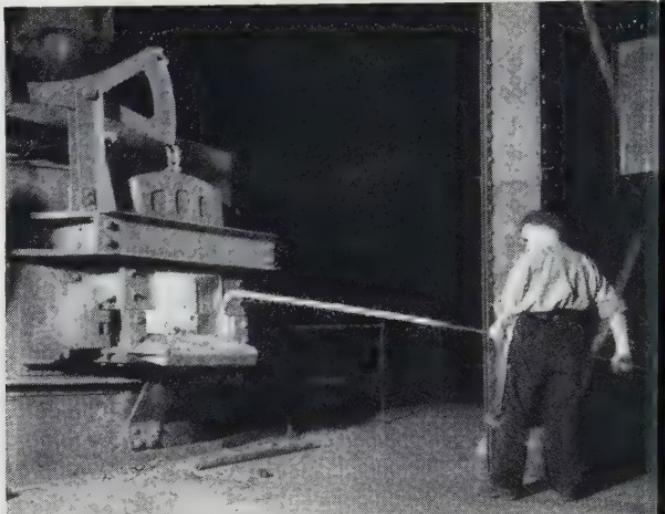
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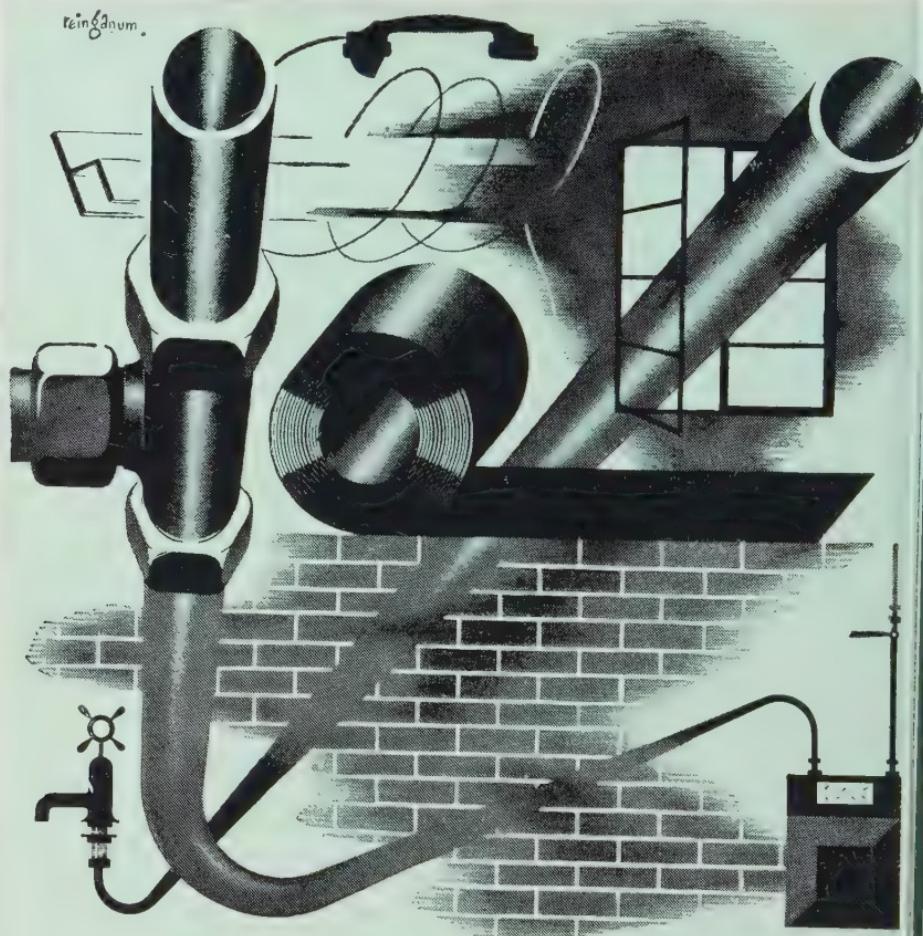
APRIL 1948

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## INSTITUTE NEWS AND ANNOUNCEMENTS

### AWARDS FOR PAPERS ON ENGINEERING ASPECTS OF NON-FERROUS METALLURGY—OFFER BY MESSRS. W. H. A. ROBERTSON AND COMPANY, LTD.

The Directors of Messrs. W. H. A. Robertson and Company, Ltd., of Bedford, having in mind the few papers contributed to the Institute's *Journal* dealing with the engineering side of non-ferrous metal production, and believing that such papers would be to the advantage of the Institute and to the industry, have offered the sum of £100 per year for at least seven years to provide an award or awards to the author or authors of such papers. The offer has been made without terms, which are left to the discretion of the Council.

The Council has accepted this offer with much gratitude, and has appointed a Committee to make recommendations as to the conditions under which the awards shall be made.

It is hoped that this most generous action by Messrs. W. H. A. Robertson and Company, Ltd., will have the effect of stimulating the writing of the type of papers that the donors have in mind.

### TECHNICAL EDUCATION OF FOREMEN AND SHOP EXECUTIVE CLASSES

The Council of the Institute has resolved, as a matter of policy, to give all possible support to the Trades Technical Societies and all corresponding societies which are concerned with such educational activities and to assist in the formation of new bodies of a like nature.

### MONOGRAPH NO. I: THE STRUCTURE OF METALS AND ALLOYS

A fifth (revised) reprint of this book, by Dr. W. Hume-Rothery, F.R.S., has now been published at 4s. 6d., post free. Each member of the Institute is entitled to receive one copy at the reduced price of 2s. 3d., post free.

### 1946 BINDING CASES

Binding cases for the 1946 volumes of the *Journal* and of *Metallurgical Abstracts* are now available, and will be supplied free on demand to all who possess the 1946 issues of these publications. The cases have been despatched to members who have already requested them.

## NEWS AND ANNOUNCEMENTS

### COUNCIL 1948-49

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## NEWS AND ANNOUNCEMENTS

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T. M. HERBERT, M.A., Scientific Research Manager, Railway Executive, London Midland Region, London; Member of Council, British Non-Ferrous Metals Research Association.

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A. R. POWELL, Research Manager, Johnson, Matthey and Co., Ltd., Wembley, Msex.

C. J. SMITHILLS, M.C., D.Sc., Director of Research, The British Aluminium Co., Ltd., Gerrards Cross.

PROFESSOR F. C. THOMPSON, D.Met., M.Sc., Professor of Metallurgy, Manchester University.

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#### *Sheffield*

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## NEWS AND ANNOUNCEMENTS

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## PERSONALITIES: NEW MEMBERS OF COUNCIL

### MR. D. F. CAMPBELL, M.A., A.R.S.M.

Mr. Donald Fraser Campbell was educated at Winchester College and New College, Oxford, where he took honours degrees in

Chemistry and Mineralogy. He is an Associate of the Royal School of Mines, and was awarded the De la Beche Medal for Metallurgy. Subsequently he was engaged in the mining and smelting of copper ores in California. He was responsible, under Paul Héroult, for the construction of the first electric iron smelting furnace in the U.S.A., and was attached to the staff of the United States Steel Corporation when the electric melting of steel was first introduced there.

In 1912 he was engaged by the French Aluminium Company on the construction of large aluminium works in North Carolina, and in 1913 founded the



Company now known as the Electric Furnace Company, Ltd., of which he is Chairman. This Company introduced into England the Héroult furnace for steel-making and the Ajax-Wyatt furnace for non-ferrous metal melting. The high-frequency furnace, invented by Northrup in the United States, was first applied to commercial steel-making in Sheffield, and is now also used for the production of many metals of high melting point.

As senior partner of Campbell and Gifford, Ltd., Consulting Engineers, he was largely responsible, during the second world war, for the construction or extension of many metallurgical works, including the complete design and erection of eight mechanized

## NEWS AND ANNOUNCEMENTS

electric steel foundries. Many types of resistance furnaces, various chemical and electrochemical processes, and new equipment for heating by high frequency, have been developed by the team of metallurgists and engineers collaborating under his leadership.

Mr. Campbell is also Chairman of Davy and United Engineering Company, Ltd., Sheffield, Davy and United Roll Foundry, Ltd., Billingham, Duncan Stewart and Company, Ltd., Glasgow, and of the Metallurgical Equipment Export Company, Ltd., London. He is actively interested in the technical development of the most modern processes and equipment for metallurgical work.

He was elected a Member of the Institute of Metals in 1925; is a Fellow of the Institution of Metallurgists and of the Geological Society; a Member of the Institution of Electrical Engineers and a Member of Council of the Iron and Steel Institute.

### MR. T. M. HERBERT, M.A., M.I.Mech.E.

Mr. Thomas Martin Herbert was educated at Marlborough College and King's College, Cambridge, where he graduated in the Mechanical Sciences Tripos in 1922 and later proceeded to the Degree of M.A. He was President of the Cambridge University Engineering Society in 1921-22.

From 1922 to 1924 he served as a pupil, under the late Sir Henry Fowler, in the Locomotive Works of the Midland (later L.M.S.) Railway at Derby, after which he held an appointment from 1924 to 1928 with the British Non-Ferrous Metals Research Association, where he formed one of a team of investigators studying the causes of the wastage of copper locomotive firebox stays.

He returned to the London, Midland and Scottish Railway in 1928 as Research Assistant in the Chief Mechanical Engineer's Department, in 1930 became Secretary of the Company's Advisory Committee on Scientific Research, and subsequently, in 1932, he was appointed Scientific Research Manager in charge of the Company's laboratories. He was largely responsible for the gradual expansion of the Company's research facilities, and for the design of the new laboratories, completed at Derby in 1935.

Mr. Herbert was elected a member of the Institute of Metals in 1932, and is a member of the Institution of Mechanical Engineers, whose George Stephenson Research Prize he was awarded in 1928. He is also a member of the Councils of the British Cast



Iron Research Association and of the British Non-Ferrous Metals Research Association, Vice-Chairman of the Corrosion Committee of the British Iron and Steel Research Association, and Honorary Secretary of the Association of Special Libraries and Information Bureaux.

## MR. A. R. POWELL

Mr. Alan Richard Powell was born in London on 6 March 1894, and was educated at the City of London School; subsequently he attended evening classes in metallurgy at the Sir John Cass

Technical Institute, obtaining a diploma and research prize in 1916.

In 1913 he joined G. T. Holloway and Company, Ltd., as Assistant Chemist, for training in process metallurgy and metallurgical analysis, and was their Chief Chemist from 1916 until 1918, when he was appointed Research Chemist to Johnson, Matthey and Company, Ltd., to start their Research Department. He has been Research Manager to the firm since 1921—first at Hatton Garden, and later (since 1938) at their new Research Laboratories at Wembley.

Mr. Powell has for many years specialized in the precious metals and rarer base metals, being responsible for new methods of refining and analysing the platinum metals and for recovering them from their ores. In recent years he

has developed methods for the preparation of highly purified metals for fundamental research work, and has also worked on brazing and electroplating problems. In collaboration with the late Dr. W. R. Schoeller, for 15 years he carried out investigations on the methods of analysis of the earth acids and other analytical processes dealing with tungsten, tin, nickel, cobalt, and the precious metals. He is part author, with Dr. Schoeller, of a book on "Analysis of Minerals and Ores of the Rarer Metals", a third edition of which is now in the press, and has published numerous papers in *The Analyst* on the analytical chemistry of cobalt, nickel, tantalum, niobium, zirconium, titanium, &c.

From 1927 to 1930 Mr. Powell was Lecturer in Metallurgical Analysis and Assaying at the Sir John Cass Technical Institute. He has been an abstractor and reviewer for the Institute of Metals since 1923 and an abstractor for the Bureau of Chemical Abstracts



## NEWS AND ANNOUNCEMENTS

since 1920. In 1947 he became Sub-Editor of the Metallurgy and Inorganic Chemistry Sections of British Chemical Abstracts.

He was elected a Member of the Institute of Metals in 1923, and is a Fellow of the Institution of Metallurgists, a Fellow of the Chemical Society, and a member of the Society of Chemical Industry.

### INSTITUTE OF METALS (PLATINUM) MEDAL

The Institute of Metals Medal has been awarded annually since 1938 in recognition of outstanding services to the non-ferrous industries, whether on the industrial or scientific side, without distinction of race or country. The medal (a picture of which is given below) was designed by Mr. Harold Stabler, R.D.I., and is placed at the disposal of the Council of the Institute by The Mond Nickel Company, Ltd.



The medal, which is of pure platinum, is prepared at The Mond Nickel Company's precious metal refinery at Acton. On the obverse, the medal shows the bust of a female figure, who holds high a laurel wreath, and around the outside is inscribed "Award of the Institute of Metals". The design on the reverse symbolizes metallurgical research, and consists of three intertwined links. In the top link "research" is represented by a microscope, and the two lower ones represent the two directions that research may take—"science", symbolized by a wash-bottle and filter, and "industry", symbolized by a factory building. On the surrounding border is the inscription "For Distinguished Services to Non-Ferrous Metallurgy".

Awards of the medal have been made as follows :

1938. Professor Sir William Bragg, O.M., K.B.E., M.A., D.Sc., P.R.S.

1939. Professor Sir Harold Carpenter, M.A., Ph.D., D.Sc., D.Met., A.R.S.M., F.R.S.

1940. Paul D. Merica, Ph.D., D.Sc.

1941. Cecil H. Desch, D.Sc., LL.D., Ph.D., F.R.S.

1942. W. (now Sir William) Murray Morrison.

## NEWS AND ANNOUNCEMENTS

1943. Harold Moore, C.B.E., D.Sc., Ph.D.  
1944. The Hon. R. M. Preston, D.S.O.  
1945. Richard Seligman, Ph.nat.D.  
1946. Lieut.-Colonel Sir John Greenly, K.C.M.G., C.B.E.,  
M.A.  
1947. John L. Haughton, D.Sc., and Marie L. V. Gayler,  
D.Sc. (Mrs. Haughton), jointly.  
1948. Robert C. Stanley, M.E., E.M., Sc.D., D.Eng.
- 

## LETTER TO THE EDITOR

### 1948 AUTUMN MEETING IN CAMBRIDGE

SIR,

The Institute of Metals is to meet at Cambridge between 14 and 17 September. Had I known of this earlier, it would have been a pleasure to have organized—subject to the Council's approval—an exhibition showing the past work of the Corrosion Research Section, and to have been present in person to discuss the exhibits with members. Unfortunately, however, when first I heard of the meeting, I had already arranged to be in the North of England during that period, and shall have to leave Cambridge by a late train on Monday, 13 September.

It has been suggested to me, however, that some members may arrive in Cambridge a day or two before the meeting. I should, therefore, be glad to arrange for such an exhibition to take place on the afternoon of Monday, 13 September, at 2.30 p.m., when I could be present to receive visitors in person, and possibly give an informal talk on the exhibits. It will be possible for the exhibition to remain open to members on Tuesday, 14 September. The place will be the Goldsmiths' Laboratory.

Members should understand, of course, that this exhibition will not form part of the Institute's official meeting, but is arranged to take advantage of the presence of members of the Institute in Cambridge at that time. It would be necessary for any Member who proposed to arrive a day early, to make his own arrangements with an hotel.

It would be a convenience to know how many members are likely to be present on the Monday, and perhaps those who intend to come that day would very kindly send me a postcard at this address about a week before the time. This need not deter others who have not sent a postcard from attending if, at the last moment, they find that they can do so. I am doubtful, however, whether it would be worth while for anyone to arrive a day early simply for this purpose, especially since the exhibition will be open on the Tuesday. It should be explained that the exhibition may be of a less ambitious character than the corrosion exhibitions held in the past when scientific associations have visited Cambridge. It happens that several of my collaborators are leaving me this summer, and, although others will be taking their place, they will not have begun to produce results by September. Thus the exhibition will represent past rather than present research; of our older exhibits, some will already be known to certain members of the Institute, while others have deteriorated in storage. I feel it right

## NEWS AND ANNOUNCEMENTS

to add this warning in order that those who attend may not be disappointed. If, nevertheless, a few members do care to come in on the Monday, it will be a very special personal pleasure to myself and such of my colleagues as are still here.

Yours, &c.,

ULICK R. EVANS.

*Department of Metallurgy,  
Pembroke Street,  
Cambridge,  
5 March 1948.*

## PERSONAL NOTES

MR. NORMAN ALLEN has left the English Electric Co., Ltd., Stafford, and is now engaged as Metallurgist with A. C. Wickman, Ltd., Coventry, undertaking development work and process control.

MR. BANI R. BANERJEE, B.Met., has left Yale University to join the Faculty of the Illinois Institute of Technology, Chicago, in the Department of Metallurgical Engineering.

DR. W. BOAS, of the Section of Tribophysics, University of Melbourne, expects to be in England from the end of August until the end of October this year.

DR. F. P. BOWDEN has been elected a Fellow of the Royal Society. He is distinguished for his researches on friction and lubrication.

MR. D. J. O. BRANDT, B.Sc., A.R.S.M., A.I.M., is now with the British Iron and Steel Research Association, 11 Park Lane, London, W.1.

DR. C. H. DESCH, F.R.S., recently visited Belgium, where he lectured for the British Council at Ghent and other Universities on "Recent Advances in Steel".

DR. S. F. DOREY, C.B.E., Wh.Ex., a Vice-President of the Institute, has been elected a Fellow of the Royal Society. Dr. Dorey, some biographical notes of whom were published in the last issue of the monthly *Journal*, is distinguished for his contributions to marine engineering.

DR. GEORGE DREVER, B.Sc., has left Barr and Stroud, Ltd., Glasgow, and is now with the Research and Development Department of The Walterisation Co., Ltd., The Knoll, South Holmwood, Dorking, Surrey.

MR. I. M. I. EL-SHERIF, M.Sc., has returned to Egypt; his address is 88 Sharia Badī, Choubra, Cairo.

MR. S. E. FLACK has now retired as Managing Director of Bull's Metal and Melloid Co., Ltd., Yoker, Glasgow; correspondence should be addressed to him at Beechrise, Drumchapel, Glasgow.

DR. F. A. FOX gave a talk on 1 April in the B.B.C. "Science Survey" Series, on magnesium.

## NEWS AND ANNOUNCEMENTS

MR. F. M. GARNHAM, an Original Member of the Institute, has been elected President of the National Association of Non-Ferrous Scrap Metal Merchants for a second term.

DR. F. JOHNSON, who retired last year from the Metallurgical Department of the Birmingham Central Technical College, received a presentation of books at the annual dinner of the Birmingham Metallurgical Society on 18 March. The President of the Society, in making the presentation, paid a tribute to Dr. Johnson's work for the College and also for the Society, of which he is a Past-President and has been elected an Honorary Member.

MR. A. CRAIG MACDONALD, B.Sc., F.I.M., M.I.Mech.E., Chief Metallurgist, Albion Motors, Ltd., Glasgow, and Chairman of the Scottish Local Section of the Institute, has been elected a Fellow of the Royal Institute of Chemistry.

MR. J. MCNEIL, A.R.T.C., Technical Representative in India of The Mond Nickel Co., Ltd., left Bombay in March for about 5 months' leave. While in England, his address will be c/o Grindlay's Bank, Ltd., 54 Parliament St., London, S.W.1.

MR. B. PODCZASKI, Dipl. Ing., resigned his post as Assistant Professor at the Polish University, London, with effect from 1 March 1948, and has left England for Buenos Aires, to take up the appointment of Metallurgical Adviser to the Argentine Fabricacione Militares.

MR. R. L. RICHARDS, B.Met.E., left Australia for London in March on the s.s. *Strathand*, for an indefinite period.

MR. ROBERT C. STANLEY, Chairman and President of the International Nickel Company of Canada, Ltd., expects to arrive in England on 13 May.

MR. A. W. TAYLOR, A.I.M., is now with the Arc Manufacturing Co., Ltd., 52a Goldhawk Rd., Shepherd's Bush, London, S.W.12 (*not* 529 Goldhawk Rd., as printed on p. xxxiii of the Dec. 1947 issue of the *Journal*).

MR. W. S. TURPIN, B.Sc., A.I.M., recently resigned his post as Metallurgical Assistant to the Chief Chemist, British Railways, Western Region, Swindon, and has taken up an appointment as Metallurgist and Technical Manager with Grey and Marten, Ltd., City Lead Works, Southwark Bridge, London, S.E.1.

MR. P. L. WILLMOTT is now employed as Metallurgical Chemist with Locke Lancaster and W. W. and R. Johnson, Ltd., Millwall Lead Works, 308 West Ferry Rd., Millwall, London, E.14.

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*Note* : Will members (in addition to informing the Institute's administrative department of changes of address, occupation, &c.) kindly notify the Editor, separately, of all changes of occupation, appointments, awards of honours and degrees, &c., as these are matters which interest their fellow members. Such notes should reach the Editor not later than the 21st day of each month, for publication in the next month's issue.

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## NEWS AND ANNOUNCEMENTS

### ELECTION OF ORDINARY MEMBERS, ASSOCIATE MEMBER, AND STUDENT MEMBERS

The undermentioned 22 Ordinary Members, 1 Associate Member, and 19 Student Members were elected on 31 March 1948.

#### As Ordinary Members

- BEZBORA, Nagendra Nath, B.Sc. (Met.), Metallurgist, Laboratory, Hoffmann Manufacturing Company, Ltd., Chelmsford, Essex.
- BLEST, Frank Ernest David, Chemist, The Ever-Ready Company (Great Britain), Ltd., Canal Works, Walsall Street, Wolverhampton.
- BOSSENKOOL, Helmich W., M.E., Vice-President and Director of Research, General Plate Division, Metals and Controls Corporation, Attleboro, Mass., U.S.A.
- BRASUNAS, Anton de Sales, Department of Metallurgy, Massachusetts Institute of Technology, Cambridge 39, Mass., U.S.A.
- CAHILL, Michael Melvin, Metallurgical Chemist, Box 67, Mine Club, Broken Hill, Northern Rhodesia.
- DAMERELL, Arthur G. H., M.Sc., A.R.C.S., D.I.C., Metallurgist, High Duty Alloys, Ltd., Slough, Buckinghamshire.
- EVANS, Richard Arthur Austin, Works Manager, Chemo-Metals (London), Ltd., Hirwaun Trading Estate, Hirwaun, Aberdare, Glamorganshire.
- FORWARD, Professor Frank Arthur, B.A.Sc., Head, Department of Mining and Metallurgy, University of British Columbia, Vancouver, B.C., Canada.
- GOVETT, John Romaine, Chairman, Imperial Smelting Corporation, Ltd., 37 Dover Street, London, W.1.
- HALLIWELL, Vivian Thomas Howarth, Non-Ferrous Technician, Kay and Company, Ltd., Blackhorse Street, Bolton, Lancs.
- HARDY, Leslie Staines, Works Secretary, Metals Manufacturers, Ltd., P.O. Box 21, Port Kembla, N.S.W., Australia.
- HETZIG, Reginald Alfred, Technical Information Officer and Part Editor, *Metal Powder Report*, Commonwealth House, 1-19 New Oxford Street, London, W.C.1.
- KLIMECKI, Wojciech, Dipl. Ing., Assistant Lecturer, University School of Mining and Metallurgy, Cracow, Poland.
- KOPEC, Ing. Rudolf, Research Engineer, 31 Londýnská, Prague XII, Czechoslovakia.
- KRUPKOWSKI, Professor Aleksander, Ing. Met., D.Sc., Mining Academy, Cracow, ul. Krzemionki 11, Poland.
- LOWMASS, Arthur John, Technical Assistant, E. Silver and Company, 80 New Bond Street, London, W.1.
- McPHERSON, Norman, B.Sc., General Manager, The Aluminium Corporation, Ltd., Dolgarrog, Conway, Caernarvonshire.
- MAŠL, Ing. Karel, Chief of the Research Institute of Metals, Czechoslovak Metallurgical Works, Panenske Brézany, pp. Odolená Voda, Vyzkumny Ustav Kovu, Prague, Czechoslovakia.
- SEWELL, Herbert M., A.M., A.M.L.S., Librarian, Toledo Public Library, 325 Michigan Street, Toledo 2, Ohio, U.S.A.

## NEWS AND ANNOUNCEMENTS

SKELLY, Hugh McKenna, B.Sc., Ph.D., Metallurgist, Joseph Sankey and Sons, Ltd., Manor Works, Ettingshall, Wolverhampton.

SMITH, Bernard Senior, M.Met., Lecturer in Metallurgy, Sir John Cass Technical Institute, Aldgate, London, E.C.3.

VAMBERSKÝ, Adolf, Dr. Ing., Research Assistant, Technical University, 33 Lomená, Prague XVIII, Czechoslovakia.

### As Associate Member

RUDIN, William L., B.S. (Met. Eng.), Consulting Engineer, Elesco Smelting Corporation, 1111 W. Liberty, Chicago, Ill., U.S.A.

### As Student Members

BERRY, Robert Langley Page, Student, Birmingham University.

BIGIKOCIN, Osman, Student of Metallurgy, Battersea Polytechnic, London, S.W.

BISHOP, William Charles, Assistant Metallurgist, Anglo-Celtic Watch Company, 40 Pant Street, Port Tennant, Swansea.

BROCK, Peter, B.Met., Royal Arsenal, Woolwich, London, S.E.18.

BURGESS, Norman Thomas, Student of Metallurgy, Battersea Polytechnic, London, S.W.

CHADWICK, John Dudley, Student of Metallurgy, Battersea Polytechnic, London, S.W.

CHUANG, Yu Chih, B.A.Sc., Postgraduate Student, Metallurgy Department, Liverpool University.

COCKLE, James Edwin Spencer, Student of Metallurgy, Battersea Polytechnic, London, S.W.

DARLING, Alan Sydney, Metallurgist, Johnson, Matthey and Company, Ltd., London.

EVANS, Glyn, Student of Metallurgy, Birmingham University.

EYNON, James Dennis Lascelles, Metallurgist, J. Stone and Company, Ltd., Deptford, London, S.E.14.

JONES, Herbert Dennis, Student of Metallurgy, King's College, University of Durham.

ROBBINS, Rodway Albert, Student of Metallurgy, Battersea Polytechnic, London, S.W.

SHADBOLT, Ronald William, Metallurgist, D.R. and T.D., Stewarts and Lloyds, Ltd., Corby, Northamptonshire.

STEPHENSON, Norman, B.Met.(Hons.), Ph.D., Metallurgist, Metallurgical Department, Ministry of Supply, National Gas Turbine Establishment, Whetstone, Leicester.

SYKES, Geoffrey Victor, Student of Metallurgy, Battersea Polytechnic, London, S.W.

THORLEY, Robert William, Student of Metallurgy, Birmingham University.

WEBER, Rolf, Student of Metallurgy, 73 Peter-Roth-Strasse, Basel, Switzerland.

WILLIAMS, John Randall, Metallurgist, Henry Meadows, Ltd., Wolverhampton.

## NEWS AND ANNOUNCEMENTS

### LOCAL SECTION NEWS

#### SOUTH WALES LOCAL SECTION

The following have been elected as officers of the Section for the year 1948-49:

*Chairman :*

D. W. HOPKINS, B.Sc.

*Honorary Secretary :*

K. M. SPRING.

*Honorary Treasurer :*

W. A. GRENFELL.

*Members of Committee :*

HARRY DAVIES, *Past-Chairman.*

I. S. GRANT, *Past-Chairman.*

ROOSEVELT GRIFFITHS, M.Sc., *Past-Chairman.*

E. A. HONITOR, B.Sc.

C. J. C. LEWIS, *Representing Associate Members.*

J. H. REID.

L. E. WEBB.

G. H. H. WILLIAMS, *Representing Student Members.*

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### OTHER NEWS

#### MOND NICKEL FELLOWSHIPS

As previously announced, the Mond Nickel Fellowships Committee has awarded two Fellowships for 1947 to:

*Mr. L. H. Walker* (Reynolds Tube Company, Ltd.) to study the organization and economics of light alloy production and the methods of application of group industrial research.

*Mr. D. R. G. Davies* (Richard Thomas and Baldwins, Ltd.) to study the application of statistical methods to plant metallurgical and management problems with particular reference to the steel industry.

The Committee now invites applications for the award of Mond Nickel Fellowships for the year 1948. Awards will be made to selected applicants of British nationality, educated to University degree or similar standard, though not necessarily qualified in metallurgy, who wish to undergo a course of training in industrial establishments. They will normally take the form of travelling Fellowships: awards for training at Universities may be made in special circumstances. There are no age limits, though awards will seldom be given to persons over 35 years of age. Each Fellowship will occupy one full working year. The Committee hope to award up to five Fellowships each year, of an average value of £750 each.

## NEWS AND ANNOUNCEMENTS

Mond Nickel Fellowships will be awarded in furtherance of the following objects :

- (a) To allow selected persons to pursue such training as will make them better capable of applying the results of research to the problems and processes of the British metallurgical and metal-using industries.
- (b) To increase the number of persons who, if they are subsequently employed in executive and administrative positions in the British metallurgical and metal-using industries, will be competent to appreciate the technological significance of research and its results.
- (c) To assist persons with qualifications in metallurgy to obtain additional training helpful in enabling them ultimately to assume executive and administrative positions in British metallurgical and metal-using industries.
- (d) To provide training facilities whereby persons qualified in Sciences other than Metallurgy may be attracted into the metallurgical field and may help to alleviate the shortage of qualified metallurgists available to industry.

Applicants will be required to state the programme of training in respect of which they are applying for an award, as well as particulars of their education, qualifications, and previous career. Full particulars and the necessary forms of application can be obtained from the Secretary, Mond Nickel Fellowships Committee, 4 Grosvenor Gardens, London, S.W.1. Completed application forms will be required to reach the Secretary of the Committee not later than 1 June 1948.

### THE UNIVERSITY OF BIRMINGHAM : OPEN SCHOLARSHIPS IN METALLURGY

Six scholarships of the annual value of £50, tenable for three years in the Department of Metallurgy, will be awarded in 1948. These scholarships are eligible for supplementation by the Ministry of Education. The Ministry is prepared to add a maintenance allowance in each case which will be based on a means test. Applicants must have complied with the requirements of the Joint Matriculation Board for entry upon a degree course, and should possess the Higher School Certificate of a recognized examining body, or be candidates for such certificates in the year in which they are candidates for the scholarship. Alternatively, candidates may possess the Intermediate B.Sc. degree of the University of London, or be candidates for the examination in the year of the award of the scholarship.

Candidates for the scholarship must present, or have presented, chemistry, physics, and mathematics at the Higher School Certificate Examination or London Intermediate Examination, two at least of these subjects being at principal or group standard. A Metallurgy Scholarship cannot be held along with a State Scholarship or any similar award of comparable value, or by a student in the Education Department under the regulations for the Training of Teachers. The continuance of the scholarship will be subject to satisfactory reports on the scholar's work and conduct.

Scholars will be expected to begin their University course in October 1948. Applications for the scholarships (which are

## NEWS AND ANNOUNCEMENTS

restricted to candidates of British nationality born not earlier than 1 January 1923), should be forwarded to the Registrar of the University of Birmingham not later than 30 June 1948. (A form of application and syllabus of the Faculty of Science can be obtained from the Registrar.) Final acceptance of each candidate is subject to the approval of the Joint Recruiting Board.

### FOUNDERS' COMPANY FELLOWSHIPS

The Worshipful Company of Founders of the City of London, believing that the development and progress of founding and the science of metallurgy must depend very largely on attracting to the industry highly trained men of evident talent, awards Fellowships so as to give facilities for advanced education to men who have already completed their normal course of training, such training to have been at a University or to be at least of a high educational standard. These "Founders' Company Fellowships" are available to those candidates who appear likely to be able to make good their careers in the founding industry if afforded the facilities for further courses of study designed specially to qualify them towards that end.

Fellows are chosen from among applicants who have completed such training as mentioned above, in chemistry, physics, metallurgy (most especially in connection with molten metal), and allied sciences. In addition, some practical foundry training and experience, together with, if and when possible, the Diploma of the British Foundry School would carry weight with the Selection Committee. The Committee pays considerable attention to the character and powers of initiative of the candidate.

The course to be followed by the Fellow will in each case be chosen with the object of adding to his scientific equipment that which appears to be most necessary for adapting him to some branch of the founding industry. There will be no limitation to the nature of the course which may be selected ; it might include research, a period in works, or foreign experience, due regard being paid to the wishes and aptitude of the Fellow.

The normal value of the Fellowship is £300 p.a., and it will be renewable for a second year and, in special cases, for a third year. Payment will be made monthly, in advance.

The Fellow will be expected to devote his whole time to work approved by the Company, and to submit periodical reports of progress if required. No other work for which payment would be received may be undertaken without the consent of the Master of the Company, and no other grant, Scholarship, or Fellowship may be held concurrently with the Fellowship unless the Selection Committee approves.

Candidates must be not less than 21 years of age on 1 September of the year of application. The tenure of the Fellowship dates from 1 September.

Applications must be submitted by 1 May to the Clerk of the Worshipful Company of Founders, Founders' Hall, 13 St. Swithin's Lane, London, E.C.4, to whom all enquiries should be addressed.

### CHEMICAL SOCIETY RESEARCH FUND

The Council of the Society will award grants from the Research Fund in June next. Applications for Grants, to be made on forms

## NEWS AND ANNOUNCEMENTS

obtainable from the General Secretary, must be received on or before 10 May 1948; those from Fellows will receive prior consideration.

The income, arising from the donation of the Worshipful Company of Goldsmiths, is principally devoted to the encouragement of research in Inorganic and Metallurgical Chemistry.

### DISCUSSION ON THE PROTECTION OF STEEL AGAINST ATMOSPHERIC CORROSION AND MARINE FOULING

A Joint Meeting of the Iron and Steel Institute and the British Iron and Steel Research Association, to discuss several papers dealing with the protection of steel against atmospheric corrosion and marine fouling, will be held at 4 Grosvenor Gardens, London, S.W.1, on Thursday, 17 June 1948. Mr. T. M. Herbert, Deputy Chairman of the Corrosion Committee and Chairman of the Protective Coatings Sub-Committee, will preside at the morning session (10.0 a.m. to 12.45 p.m.), and Professor J. E. Harris, Chairman of the Marine Corrosion Sub-Committee, at the afternoon session (2.15 to 4.30 p.m.) Members of the Institute of Metals will be welcome to attend the meeting.

A buffet lunch (price 6s.) will be served from 12.45 to 2.15 p.m.; applications for tickets should be made not later than 15 June.

Separate reprints of the papers are obtainable for 2s. 6d. each, or a complete set of the seven papers and a buffet lunch ticket may be had for £1. Applications should be sent to the Secretary The Iron and Steel Institute, 4 Grosvenor Gardens, London, S.W.1.

## DIARY FOR MAY

### INSTITUTE MEETING

**May Lecture**, by Professor A. O. Rankine, O.B.E., D.Sc., F.R.S., on "The Search for Minerals by Physical Methods". (Institution of Mechanical Engineers, Storey's Gate, London, S.W.1, Thursday, 13 May, at 6 p.m.)

### OTHER MEETINGS

#### MONDAY, 3 MAY

**Society of Chemical Industry, London Section**.—Dr. B. A. Southgate: "The Treatment and Disposal of Waste Waters from Industry". (Chemical Society, Burlington House, Piccadilly, W.1, at 6.30 p.m.)

#### TUESDAY, 4 MAY

**Electrodepositors' Technical Society**.—Mr. N. Christie: "Modern Nickel and Chromium Plating Practice". (James Watt Memorial Institute, Great Charles St., Birmingham, at 3 p.m.)

**Society of Chemical Industry, Chemical Engineering Group**.—Mr. J. G. Pearce: "Recent Developments in Cast Iron". (Geological Society, Burlington House, Piccadilly, London, W.1, at 5.30 p.m.)

## NEWS AND ANNOUNCEMENTS

### WEDNESDAY, 5 MAY

**Iron and Steel Institute.**—Annual General Meeting. Presentation of Bessemer Gold Medal, Sir Robert Hadfield Medal, and Williams Prize; Induction of Sir Andrew McCance as President; discussion of papers. Evening: Hatfield Memorial Lecture by Professor R. F. Mehl on "The Decomposition of Austenite by Nucleation and Growth Processes". (Royal Institution of Chartered Surveyors, Great George St., London, S.W.1, at 9.45 a.m., 2.30 p.m., and 8.30 p.m.)

### THURSDAY, 6 MAY

**Birmingham University Metallurgical Society.**—Mr. C. Smith: "The Extrusion of Aluminium Alloys". (University Buildings, Edgbaston, Birmingham, at 5 p.m.)

**Iron and Steel Institute.**—Annual General Meeting; discussion of papers continued. (Royal Institution of Chartered Surveyors, Great George St., London, S.W.1, at 9.30 a.m.)

**Leeds Metallurgical Society.**—Annual General Meeting; papers by Student Members. (Main Lecture Theatre, Chemistry Dept., The University, Leeds, at 7 p.m.)

**Royal Institute of Chemistry, Sheffield, South Yorkshire and North Midlands Section.**—Annual General Meeting. (Applied Science Department, The University, Sheffield, at 6 p.m.)

### TUESDAY, 11 MAY

**Institute of Marine Engineers.**—J. W. R. Naden: "Some Metallurgical Aspects of the Manufacture of Large Tubes and Hollow forgings". (The Institute, 85 The Minories, London, E.C.3, at 5.30 p.m.)

### WEDNESDAY, 12 MAY

**Geological Society of London.**—Ordinary Evening Meeting. (Burlington House, Piccadilly, London, W.1, at 5 p.m.)

### THURSDAY, 13 MAY

**Birmingham University Metallurgical Society.**—Annual General Meeting. (University Buildings, Edgbaston, Birmingham, at 5 p.m.)

### FRIDAY, 14 MAY

**Institute of Fuel, South Wales Section.**—Annual General Meeting. (Engineers' Club, Cardiff, at 6 p.m.)

### THURSDAY, 20 MAY

**Institute of Fuel, Midland Section.**—Annual General Meeting. (Botanical Gardens, Edgbaston, Birmingham.)

**Institution of Mining and Metallurgy.**—General Meeting. (Geological Society, Burlington House, Piccadilly, London, W.1, at 5 p.m.)

### MONDAY, 24 MAY

**Electrodepositors' Technical Society.**—Mr. A. Smart and Mr. F. H. Smith: "Continuously Electroplated Steel Strip and Sheet". (Northampton Polytechnic, St. John St., Clerkenwell, London, E.C.1, at 5.30 p.m.)

## NEWS AND ANNOUNCEMENTS

TUESDAY, 25 MAY

Swansea and District Metallurgical Society.—Annual General Meeting. (Royal Institution, Swansea, at 6.30 p.m.)

### APPOINTMENTS REQUIRED

**METALLURGIST**, age 31 years, City and Guilds Certificate, 3 years prod. invests., 2 years development and research, engineering apprenticeship, 5 years toolmaking and design, desires position with prospects. Resident London area, but will move where accommodation is available. Box No. 229, Institute of Metals, 4 Grosvenor Gardens, London, S.W.1.

**METALLURGIST** (age 35), just returned to England after two years in Scandinavia, is free to consider any appointment, at home or abroad. Specialist in light alloys in all wrought forms. Reply to E. Stewart-Jones, 97 Cheyne Walk, Chelsea, London, S.W.10.

### APPOINTMENTS VACANT

*To conform to the requirements of the Control of Engagements Order, 1947, these advertisements are published for the information only of those who are "excepted persons" under the Order.*

**ASSISTANT METALLURGIST** for laboratory and factory development work in non-ferrous metals and alloys. Degree or equivalent qualification and one or two years' industrial experience. Age up to about 25 years. Salary according to age and experience. Reply with outline of qualifications and experience to Box No 227, Institute of Metals, 4 Grosvenor Gardens, London, S.W.1.

**METALLURGIST** required for general investigational work in West London factory. Experience of modern alloys and processes essential. 5-day week and Pension Scheme. Write stating age, qualifications, experience, and salary required to Box No. 230, Institute of Metals, 4 Grosvenor Gardens, London, S.W.1.

**METALLURGISTS** required for Research Laboratories. University degree or equivalent essential. Age not exceeding 30 years preferred. The salaries offered will be commensurate with qualifications and experience. Apply giving full details to Personnel Officer, High Duty Alloys, Ltd., Slough, Bucks.

**PHYSICAL METALLURGY.** Applications invited from experienced Research Graduates to take leading part in fundamental research. Apply in writing, giving details previous research experience, to Manager, Associated Electrical Industries Research Laboratory, Aldermaston Court, Aldermaston, Berks.

**THE ALUMINIUM DEVELOPMENT ASSOCIATION** requires two qualified METALLURGISTS. Knowledge of the production, fabrication, or application of aluminium and its alloys essential. Salaries, according to experience, are up to £900 per annum for the senior post and up to £600 per annum for the junior position. Superannuation scheme in operation. Applications, giving full details, should be addressed to the Technical Director, 33 Grosvenor Street, London, W.1.

**THE IMPERIAL SMELTING CORPORATION, LTD.**, non-ferrous metal, alloy, and chemical manufacturers, desire to appoint a PHYSICIST for employment in their Research Dept., Avonmouth, primarily for investigational work on X-ray crystallography and on physical analytical methods, but would also be expected to assist with Plant problems of a physical nature.

Applicants, 24-25, must have at least 2nd Class Honours Degree in Physics and appropriate industrial or research experience. The appointment is a progressive one and its scope is likely to develop. Commencing salary within the range of £500 to £750 p.a., will be according to qualifications and experience. Conditions, which include a five-day week and membership of staff superannuation scheme, are in line with best modern practice. Write for form of application to Manager, Personnel Dept., I.S.C., Ltd., Avonmouth, quoting Ref. IM/P.

**UNIVERSITY OF DURHAM.** Applications are invited for the post of PROFESSOR OF METALLURGY tenable at King's College, Newcastle-upon-Tyne. Salary £1450 p.a., with superannuation (F.S.S.U.), and family allowances. Appointment by 1 October 1948, if possible. Further particulars obtainable from the undersigned with whom applications (twelve copies) must be lodged by 28 May 1948.

W. S. ANGUS,  
Registrar, University Office, 46 North Bailey, Durham.

JUST PUBLISHED

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By WILLIAM HUME-ROTHERY, M.A., D.Sc., F.R.S.

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## NOTICE TO AUTHORS OF PAPERS

1. **Papers** will be considered for publication from non-members as well as from members of the Institute. They are accepted for publication in the *Journal* and not necessarily for presentation at any meeting of the Institute, and should be addressed to The Editor of Publications, The Institute of Metals, 4 Grosvenor Gardens, London, S.W.1.
2. **Papers suitable for publication** may be classified as :
  - (a) Papers recording the results of original research;
  - (b) First-class reviews of, or accounts of, progress in a particular field;
  - (c) Papers descriptive of works methods, or recent developments in metalurgical plant and practice.
3. **Manuscripts and illustrations** should be submitted in duplicate. MSS. must be typewritten (*double-line spacing*) on one side of the paper only, and author are required to sign a declaration that neither the paper nor a substantial part thereof has been published elsewhere. MSS. not accepted are normally returned within 3 months of receipt.
4. **Synopsis.** Every paper must have a synopsis (not exceeding 250 words in length), which, in the case of results of research, should state its objects, the ground covered, and the nature of the results. The synopsis will appear at the beginning of the paper.
5. **References** must be collected at the end of the paper, and must be numbered. Initials of authors must be given, and the Institute's official abbreviations for periodical titles (as used in *Met. Abs.*) must be used where known. Reference must be set out in the style :
  1. W. Hofmann and W. Jäniche, *Z. Metallkunde*, 1936, **28**, 1 (i.e. year volume, page).
6. **Illustrations.** Each illustration must have a number and description; only one set of numbers must be used in one paper. The set of *line figures* sent for reproduction must be drawn in Indian ink on smooth white Bristol board good-quality drawing paper, co-ordinate paper, or tracing cloth, which are preferred in the order given. Co-ordinate paper, if used, must be blue-lined with the co-ordinates to be reproduced finely drawn in Indian ink. All lettering and numerals, &c., should preferably be in *pencil*. Figures should be drawn approximately twice the size intended for reproduction. *Photographs* must be restricted in number, owing to the expense of reproduction, and trimmed to the smallest possible of the following sizes, consistent with adequate representation of the subject : 3 in. deep by 4 in. wide (two photomicrographs to a plate); 3 in. deep by  $2\frac{1}{4}$  in. wide (four to a plate); 2 in. deep by  $2\frac{1}{4}$  in. wide (six to a plate). Magnifications of photomicrographs must be given in each case. Photographs for reproduction should be loose, not pasted down (and no fastened together with a clip, which damages them), and the figure number should be written on the back of each. Legends should be given to photomicrographs, but lengthy descriptions should be avoided owing to the very limited space available on the plates. Because of restrictions on paper supplies illustrations that are not *essential* to the appreciation of the paper should not be included. Only in exceptional cases will illustrations be reproduced in already printed and readily available elsewhere.
7. **Tables or Diagrams.** Results of experiments, &c., may be given in the form of tables or figures, but (unless there are exceptional reasons) not both.
8. **Overseas Authors.** Authors resident in countries distant from Great Britain are requested to name, if possible, agents in Britain to whom may be referred matters concerning their papers, including proofs for correction. Translation from foreign languages should preferably be accompanied by a copy of the MS. in the language of the author.
9. **Reprints.** Individual authors are presented with 50, two authors with 70 and three with 90, reprints (in cover) from the *Journal*. Limited number of additional reprints can be supplied at the author's expense if ordered before proofs are passed for press. (Orders should preferably be placed when submitting MSS.)

# CRACKING DURING AND AFTER SOLIDIFICATION IN SOME ALUMINIUM-COPPER-MAGNESIUM ALLOYS OF HIGH PURITY.\*

By W. I. PUMPHREY,† M.Sc., MEMBER, and D. C. MOORE,† B.Met., STUDENT MEMBER.

(From the School of Industrial Metallurgy, University of Birmingham.)

## SYNOPSIS.

An investigation has been carried out, by means of ring-casting and restrained-weld tests, to determine the tendency for cracking to occur at temperatures both above and below the solidus during the casting and welding of aluminium-copper-magnesium alloys of high purity containing up to 12% copper and 12% magnesium.

The two types of cracking, namely cracking at temperatures above the solidus and cracking at much lower temperatures, have been distinguished during the cooling to room temperature of welds made in certain of the alloys. It is suggested that low-temperature cracking is dependent on composition, microstructure, and the degree of restraint imposed on the cooling weld. The range of alloys in which there is pronounced tendency to cracking at temperatures above the solidus extends up to about 6% copper and 6% magnesium, with a maximum in the susceptibility to cracking in ternary alloys containing approximately 1.5-2.5% copper and 1-2% magnesium. As with other systems, there appears to be a close relationship between the ternary constitutional diagram and the form of the diagram relating the cracking tendency at temperatures above the solidus with alloy content.

It is pointed out that from the practical aspect, alloys which, because of their composition, are least subject to cracking at temperatures above the solidus, are most subject to sub-solidus cracking under severe conditions of stress.

## I.—INTRODUCTION.

THE term hot-shortness has been applied to the tearing and cracking under contractional stresses which occurs in some metals and alloys at temperatures between the liquidus and the solidus during cooling from the liquid state. Hot-shortness constitutes a major metallurgical problem in both casting and welding since many of the industrially important alloys are prone to this type of failure, and in efforts to overcome this trouble much attention has been paid to the shape of castings, to mould design, and to welding technique in the welding of complex structures.

A second type of cracking which occurs at temperatures well below the solidus in castings and welds in certain alloys cooling under severe contractional stresses, may also be distinguished. This type of cracking,

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which, in the present paper, will be termed sub-solidus cracking, although less frequently encountered than hot-short cracking, can also cause difficulties in the welding of structures in which high welding stresses are likely to be developed. Cracking observed at room temperature in welded structures or in solidified castings may hence be either hot short cracking or sub-solidus cracking or a combination of both, and since the two types of cracking are due to fundamentally different causes, it is of importance to differentiate between them and to obtain some information as to the reasons for either type of cracking if a sound weld or casting is to be produced.

Previous experience suggested that the aluminium-copper-magnesium alloys might be prone to sub-solidus cracking, and, since the alloys in this system are also prone to cracking at temperatures above the solidus, an examination was made of the incidence of both types of cracking in alloys containing 0-12% copper and 0-12% magnesium. The investigation of cracking at temperatures above the solidus was carried out on similar lines to previous investigations<sup>1, 2</sup> of the hot-shortness of aluminium-rich ternary alloys.

Many industrial alloys contain both magnesium and copper, and, as such alloys form the basis of the Duralumin series, the results of the present investigation are likely to have a direct practical application from both the casting and welding aspects.

## II.—PREVIOUS WORK.

There has been little systematic investigation of the cracking during and after welding in alloys of the aluminium-copper-magnesium series, and the majority of work appears to have been carried out with particular reference to the welding properties of alloys of the Duralumin type. Many investigators state that Duralumin is not suitable for welding<sup>3, 4, 5</sup> and that alloys of this type are very subject to cracking.<sup>6</sup> It has also been reported that the tendency to cracking varies greatly with the welding process employed,<sup>3, 6, 7</sup> especially if the welds are made across the direction of rolling,<sup>8</sup> and, in addition, Knerr<sup>9</sup> found that if welds in Duralumin 0·035 in. thick were backed with steel, the consequent rapid cooling caused a continuous crack along the weld.

No differentiation appears to have been made in the literature between cracking occurring at temperatures below and cracking occurring at temperatures above the solidus, although there are numerous references to cracking in the heat-affected zones of welds made in Duralumin sheet. This latter problem is probably closely connected with the phenomenon of sub-solidus cracking.

## III.—EXPERIMENTAL WORK.

The methods used in the present work for investigating susceptibility to cracking were the same as those employed in earlier work on aluminium-silicon<sup>10</sup> and aluminium-iron-silicon alloys,<sup>1</sup> namely a restrained-weld test and a ring-casting test.

The restrained-weld test was found to be suitable for differentiating between sub-solidus cracking and cracking at temperatures above the solidus in the alloys under consideration, but because of the comparative difficulty of producing sheet material, restrained-weld tests were carried out on a small number of alloys only, with increasing total alloy contents at a constant ratio of copper to magnesium of 1 : 1. Some difficulty was encountered in the rolling of the 4%-copper + 4%-magnesium and the 6%-copper + 6%-magnesium alloys for the production of sheet for the welding tests. For the rolling of all the alloys except the 6%-copper + 6%-magnesium alloy, slabs measuring  $6\frac{1}{2} \times 4 \times \frac{9}{16}$  in. were cast. In the case of the latter alloy, a slab measuring  $12 \times 4 \times \frac{9}{16}$  in. was cast, and this slab was machined down to 0.32 in. in thickness before rolling. Both the 4%-copper + 4%-magnesium and the 6%-copper + 6%-magnesium alloys were given an initial slight cold reduction, and before subsequent rolling were water quenched from 470° C. after 24 hr. at that temperature. Rolling to the finishing thickness of 0.080 in. was carried out cold, with frequent intermediate homogenization and quenching from 470° C., the highest practicable temperature for both alloys (see Fig. 12, Plate XXVII); in order to prevent, in some measure, precipitation of brittle inter-metallic compound in the crystal boundaries. The alloys of lower total alloy content than the two mentioned above were rolled down to sheet form in the manner detailed in previous papers,<sup>1, 2, 10</sup> and in all cases the restrained-weld tests were carried out on material annealed for 1 hr. at 360° C. and cooled from that temperature at about 30° C. per hour.

Ring-casting tests were carried out on a series of 52 high-purity alloys containing up to 12% copper and 12% magnesium, covering the range of marked cracking tendency in the aluminium-copper-magnesium system. In the present investigation, the pouring temperature was standardized at 100° C. above the liquidus, determined from the appropriate equilibrium diagram.<sup>11</sup> The alloy field was covered by the rectangular-grid method, in which one alloying element in a ternary series is held constant and the other varied, and a number of curves were plotted from the results showing the effect on cracking of simultaneous and independent variation of the magnesium and copper contents.

Microscopic examination was made of the weld and weld area of the welded alloys and of the structures of the corresponding alloys cast in ring form.

#### IV.—EXPERIMENTAL RESULTS.

##### 1. *Restrained Welds.*

Restrained-weld tests were carried out on five alloys with increasing total alloy contents containing equal amounts of copper and magnesium, four tests being made on each alloy. The first tests made on the 4%-copper + 4%-magnesium alloy and the 6%-copper + 6%-magnesium alloy indicated that both alloys were prone to sub-solidus cracking. Such cracking occurred with some violence along the length of the weld bead in either alloy when the temperature of the weld had fallen to about 200° C. It was observed that no cracking of the normal supersolidus type had occurred in the 6%-copper + 6%-magnesium alloy and only a small amount in the 4%-copper + 4%-magnesium alloy before the incidence of the sub-solidus cracking, and that sub-solidus cracking in the former alloy was far more serious than in the latter. It should here be mentioned that there was no indication of sub-solidus cracking in any of the alloys examined by the ring-casting test; the probable reasons for this will be discussed later.

In order to differentiate cracking at temperatures above the solidus from that occurring below the solidus in the two alloys mentioned above, further welds made in these alloys were removed from the restraining jig before the occurrence of the sub-solidus cracking. The remaining three alloys, containing 0·5% copper + 0·5% magnesium, 1·0% copper + 1·0% magnesium, and 2·0% copper + 2·0% magnesium, were allowed to cool in the jig in the normal manner after welding.

In all cases, measurements were made of the total length of cracking occurring on both sides of the welded sheets after removal from the jig. The average length of cracking encountered in each alloy is shown plotted in Fig. 1 (a). For purposes of comparison, the amount of cracking encountered in alloys of the same composition examined by the ring-casting method are plotted in Fig. 1 (b). The two curves are markedly similar, although the rate of increase in susceptibility to cracking with increase in the total alloy content is greater in the welds than in the ring castings, and the maximum of the curve occurs at a slightly lower alloy content with the former method of testing. The close agreement between Figs. 1 (a) and 1 (b) indicates that in the alloy series at present under consideration the probability of cracking occurring at temperatures above the solidus during welding can be estimated with reasonable accuracy from a knowledge of the ring-casting results.

Under practical conditions of welding, however, the close correlation between the two tests is likely to be somewhat vitiated by the incidence of cracking at temperatures below the solidus in alloys containing more than 4% copper and 4% magnesium.

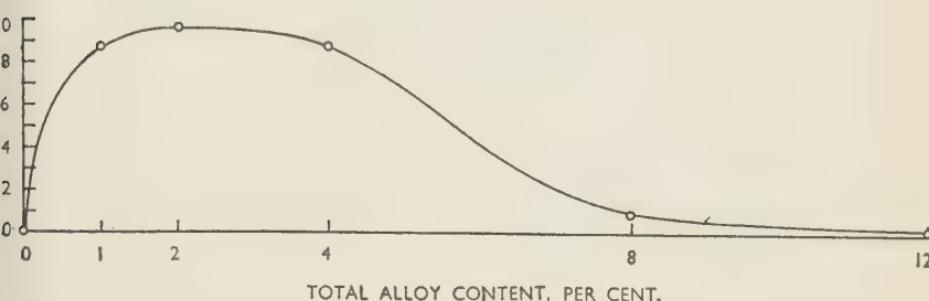


FIG. 1 (a).—Cracking of Welds in Alloys Containing Equal Amounts of Copper and Magnesium.

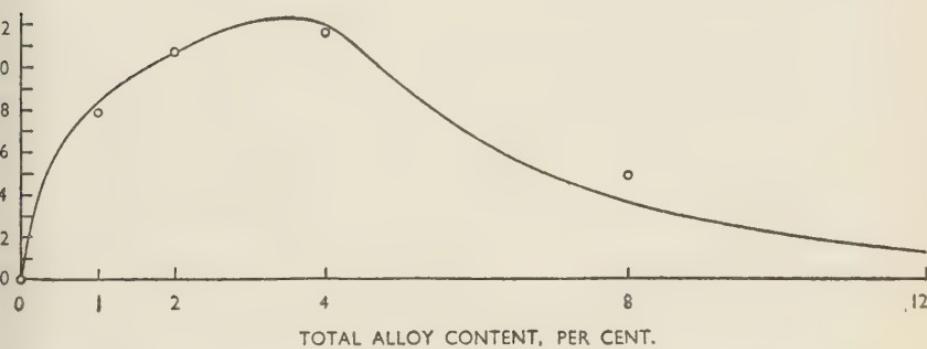


FIG. 1 (b).—Cracking of Ring Castings in Alloys Containing Equal Amounts of Copper and Magnesium.

## 2. Ring Castings.

The results of the ring-casting tests are plotted in Figs. 2-5. Fig. 2 shows the effect on the cracking of ternary alloys of increase in the magnesium percentage while maintaining a constant copper content; and Fig. 3, the effect on cracking of increasing additions of copper to a ternary alloy of constant magnesium content. Fig. 4, constructed from Figs. 2 and 3, represents, by means of contours, the severity of cracking over the whole of the ternary field investigated. Fig. 5 shows an enlarged portion of the ternary diagram of cracking, in which the position of the contours near the aluminium corner can be seen more clearly.

The curves in Fig. 2 at constant copper contents show a marked resemblance to one another up to 4.0% copper, indicating, as the

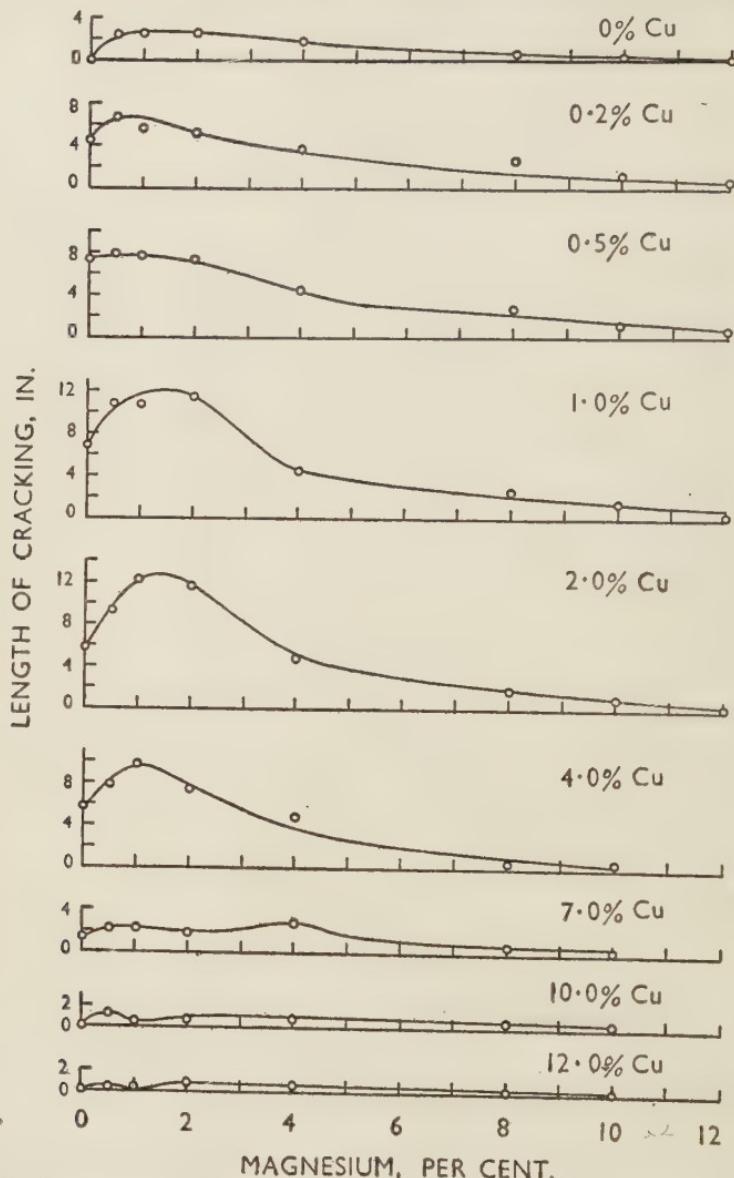


FIG. 2.—Variation of Cracking with Increasing Magnesium Percentage in Alloys of Constant Copper Contents.

magnesium is increased, a sudden rise in crack severity, followed by a gradual decrease. The curves at 7.0, 10.0, and 12.0% copper show, as

do the previous curves, an initial increase in cracking, but instead of then showing a simple decrease, these curves exhibit a second maximum

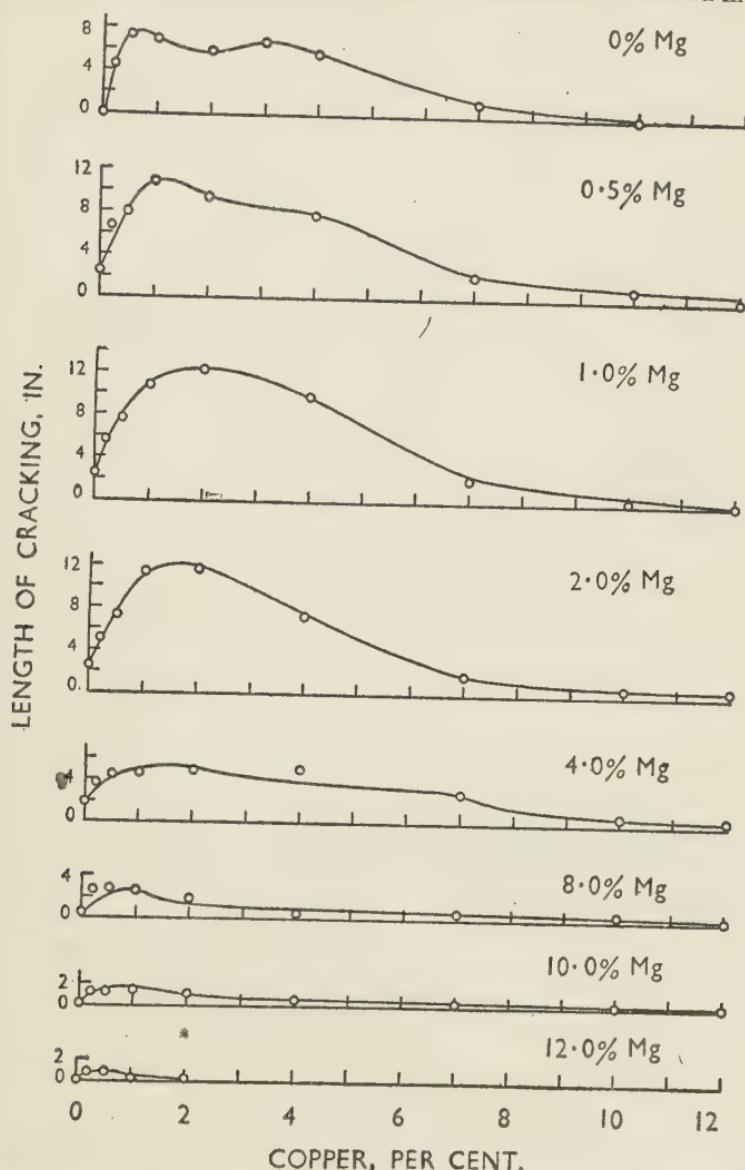


FIG. 3.—Variation of Cracking with Increasing Copper Percentage in Alloys of Constant Magnesium Contents.

before the gradual decrease occurs. The maximum amount of cracking in this series of curves increases as the copper content is increased from 2% to 20%, followed by a decrease up to a copper content of 12%. In all

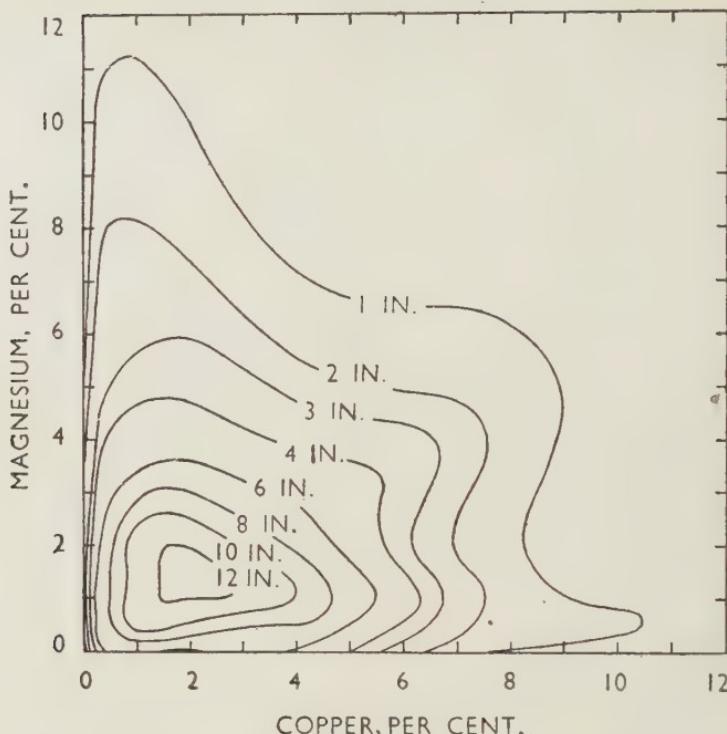


FIG. 4.—Ternary Diagram of Cracking for Ring Castings.

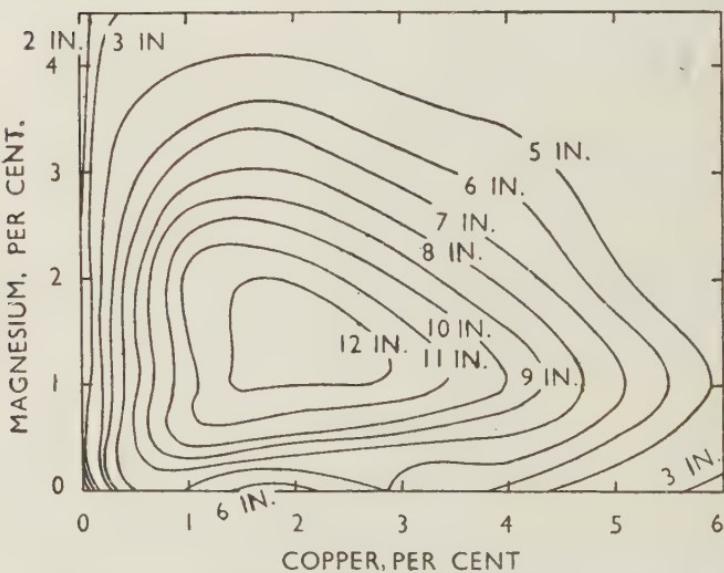
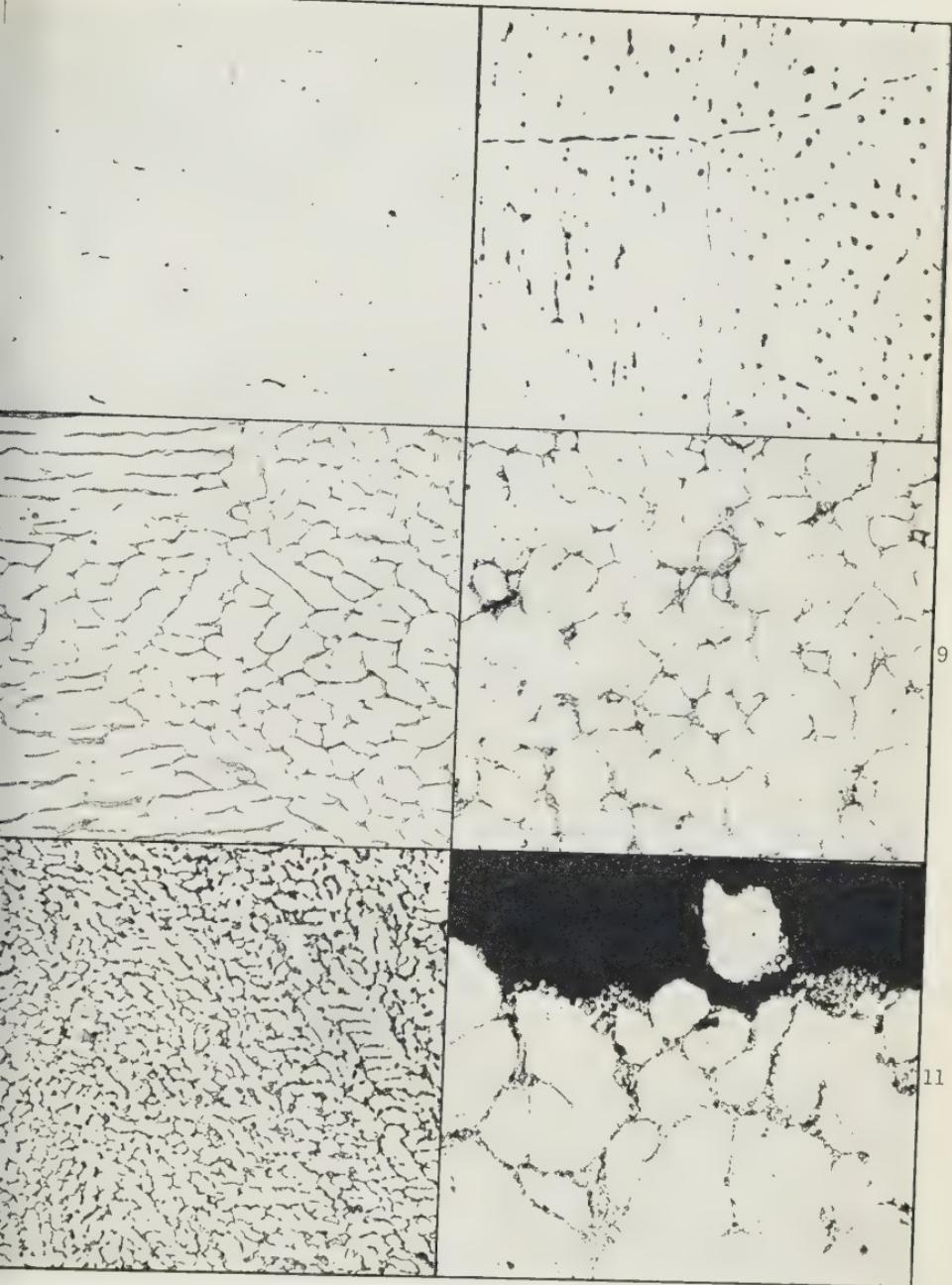


FIG. 5.—Composition Ranges in which Cracking is Greatest in Ring Castings.

6.—Ring Casting in 1·0%-Copper + 1·0%-Magnesium Alloy.  $\times 200$ .7.—Ring Casting in 2·0%-Copper + 2·0%-Magnesium Alloy.  $\times 200$ .8.—Ring Casting in 4·0%-Copper + 4·0% Magnesium Alloy.  $\times 200$ .9.—Weld in 4·0%-Copper + 4·0%-Magnesium Alloy.  $\times 200$ .10.—Weld in 10·0%-Copper + 10·0%-Magnesium Alloy.  $\times 200$ .11.—Fracture in Tensile-Test Specimen Taken from Weld in 6·0%-Copper + 6·0%-Magnesium Alloy.  $\times 500$ .All etched in conc.  $\text{HNO}_3$ .

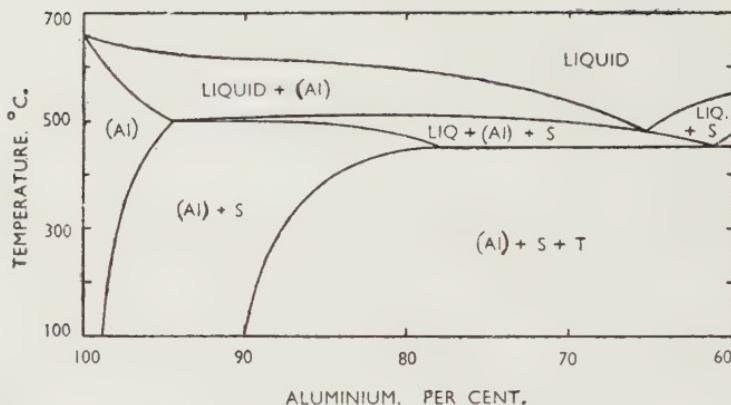


FIG. 12.—Section at the Constant Ratio of Copper to Magnesium of 1:1, from the Ternary Equilibrium Diagram Aluminium-Copper-Magnesium (Nishimura).

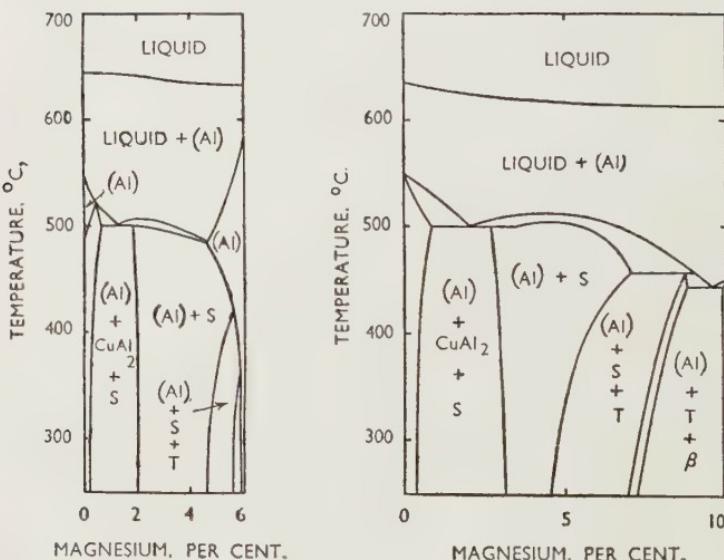


FIG. 13 (a).—Section at Constant Aluminium Content of 94% (Nishimura).

FIG. 13 (b).—Section at Constant Aluminium Content of 90% (Nishimura).

cases, cracking reaches a small value at about 10–12% magnesium. The sections in Fig. 3 at fixed magnesium percentages are of general binary-curve form, and no double maximum occurs except in the case of the binary aluminium–copper alloys; the presence of this double maximum has, however, already been commented on.<sup>2</sup> The rise in the maximum amount of cracking with increasing magnesium content is evident, the maximum cracking occurring at a constant magnesium content of 1·0%. Cracking in all the sections in Fig. 3 reaches a small value at a copper content of 10–12%.

The ternary diagrams of cracking in Figs. 4 and 5 indicate a maximum in the susceptibility to cracking at approximately 1·5–2·5% copper and 1–2% magnesium, with a decrease in the intensity of cracking on all sides of this composition range.

In general, except close to the two binary axes, a combined percentage of copper and magnesium in excess of 12% ensures negligible cracking. From Figs. 4 and 5, alloys of the Duralumin type, containing 2·5–4% copper and up to 1% magnesium, would be expected to exhibit severe weld cracking. This result is in accordance with reported industrial experience.

As has already been mentioned, no sub-solidus cracking was observed in any of the alloys examined by the ring-casting test. Sub-solidus cracking can be differentiated from cracking which occurs at temperatures above the solidus by visual examination of the surface of the fracture. In the latter instance, the fracture surface is of the same colour as the metal itself, and generally presents a bright appearance, while the surface of a crack which forms below the solidus is much darker in colour than the metal and has a characteristic brittle appearance. Examination of the surfaces of the cracks in representative samples of all the ring castings indicated that in all cases cracking was of the supra-solidus type.

### 3. Microscopic Examination.

Microscopic examination was made of sections through the welds in all the alloys examined by the restrained-weld test and through the ring castings of the corresponding alloys. In both ring castings (Fig. 6, Plate XXVI) and welds, the first slight occurrence of a second phase was observed in the alloy containing 1% copper and 1% magnesium. The second phase, however, was present in rather larger quantities and in more pronounced boundary form in the welds than in the castings. The 2%-copper + 2%-magnesium alloys were similar with regard to the amount of second phase present; in the casting, however (Fig. 7, Plate XXVI), the phase was present both within the crystals and at the

boundaries, while in the weld the second phase was almost entirely in boundary form. The 4%-copper + 4%-magnesium alloys were essentially identical, both as regards the amount of intermetallic compound present and its occurrence; in both cases the second phase was present in a practically continuous boundary network (see Figs. 8 and 9, Plate XXVI). Increase in the amount of intermetallic compound present and decrease in the size of the primary crystals occurred with further increase in total alloy content, the intermetallic compound in both castings and welds being present in continuous boundary form (Fig. 10, Plate XXVI). A third phase was observed in the alloy containing 10% copper and 10% magnesium.

#### V.—THEORETICAL CONSIDERATIONS.

In the aluminium-copper-magnesium system, two types of cracking, namely cracking at temperatures between the liquidus and solidus and cracking at temperatures below the solidus, can be distinguished during the cooling to room temperature of welds made in these alloys. The probability of the occurrence of the former type of cracking can be estimated by an examination of the ring-casting results plotted in Fig. 4. The occurrence of sub-solidus cracking would seem to be a function of both the composition and the microstructure, but it is possible that the two types of cracking are associated, since small cracks formed at temperatures above the solidus may on cooling to lower temperatures cause local concentrations of stress sufficient to initiate sub-solidus cracking.

##### 1. *Sub-Solidus Cracking.*

Cracking was observed to take place with some violence in welded test plates of both the 4%-copper + 4%-magnesium and the 6%-copper + 6%-magnesium alloys when the temperature of the weld had fallen to about 200° C. This cracking was far more severe in the latter alloy than in the former, and no sub-solidus cracking was observed in alloys of lower total alloy content. It seems reasonable to associate the incidence of cracking below the solidus with the first appearance of second phase in more or less continuous boundary form. Intermetallic compound precipitated in this form during the cooling from the liquid state would weaken the crystal boundaries, causing boundary fracture to occur due to the high stresses across the weld arising at low temperatures from the thermal contraction of the test plates. Cracking occurring for such a reason would be expected to increase in severity with increase in the completeness of the outlining of the crystal boundaries by the second phase, and consideration of the results of the microscopic exami-

nation indicates why there was no observable sub-solidus cracking in the 2%-copper + 2%-magnesium alloy, some in the 4%-copper + 4%-magnesium alloy, and still more in the 6%-copper + 6%-magnesium alloy.

In order to confirm whether, in fact, fracture occurred preferentially at the crystal boundaries in the presence of the outlining phase, a tensile test was carried out on a weld made without external restraint between two test sheets of the 6%-copper + 6%-magnesium alloy. The results indicated that the alloy had practically no ductility, the elongation on a 2-in. gauge length being of the order of 1-2%. Microscopic examination of the fracture indicated that fracture had occurred entirely at the crystal boundaries and that there was no distortion of the crystals in the region of the fracture; the appearance of the fracture is shown in Fig. 11 (Plate XXVI).

The occurrence of cracking below the solidus would seem to be dependent on both composition and microstructure, and no such cracking would be expected in alloys in which separation of the second phase in boundary form does not occur. Sub-solidus cracking is also dependent on the stress applied to the alloy during cooling, and this type of cracking would not be expected in any aluminium alloy in the complete absence of stress at sub-solidus temperatures.

As has been mentioned, there was no indication of sub-solidus cracking in any of the alloys examined by the ring-casting test. This may be due to the smaller stress in the metal in the ring-casting test when the material has negligible ductility.

## 2. Cracking at Temperatures Above the Solidus.

For the interpretation of the ring-casting test results, a consideration of the constitutional diagram representing the state of the alloys in metastable conditions is of interest. In the diagram proposed by Nishimura<sup>12</sup> for the aluminium-copper-magnesium system, the compositional limits for the solid-solution range in the aluminium corner of the diagram are lower than those indicated by Vogel<sup>13</sup> and considerably lower than those given by Ôtani.<sup>14</sup> It would thus seem probable that the form of the diagram proposed by Nishimura approximately represents the constitution of the alloys in the cast state, and hence is of value for the interpretation of the ring-casting results. Nishimura has presented a number of radial sections radiating from the aluminium corner of the aluminium-copper-magnesium diagram. These sections, which are at constant ratios of copper to magnesium, are of similar simple form up to a combined percentage of magnesium and copper of 7%, having a maximum in the  $\alpha$  solid-solubility range at

a combined alloy content of approximately 6% (see Fig. 12, Plate XXVII).

From the complete ternary constitutional diagram, the maximum in the solidus-liquidus temperature interval occurs at an alloy content of approximately 3·5% copper and 2·5% magnesium. From previous theoretical reasoning,<sup>1, 2, 10</sup> a maximum in the tendency to cracking would hence be expected at this composition. In actual fact, the maximum cracking is obtained in an alloy of slightly lower copper and magnesium content. The difference in the precise positions of the maxima is, however, probably due to differences in the extent of metastability of the ring-casting alloys and the alloys examined by Nishimura, since in the ring castings the first appearance of the second phase in the alloys containing equal percentages of copper and magnesium was noted in the 1%-copper + 1%-magnesium alloy, a result not in exact accordance with the less metastable section shown in Fig. 12 (Plate XXVII).

Sections through the constitutional diagram indicate a rapid decrease in the solidus temperature (an increase in the liquidus-solidus interval) with the initial additions of copper to an aluminium-magnesium alloy or magnesium to an aluminium-copper alloy. This is in agreement with the ring-casting results.

Two sections through the aluminium-copper-magnesium diagram, at constant aluminium contents of 94 and 90%, given by Nishimura, are reproduced in Figs. 13 (a) and 13 (b) (Plate XXVII), respectively. These sections are, in effect, sections along the lines joining the 6%-magnesium and 6%-copper points and the 10%-magnesium and 10%-copper points in Fig. 4. In the section at 94% aluminium (Fig. 13 (a)), the first replacement by magnesium of the copper in an aluminium-copper alloy containing 6% copper, or of magnesium by copper in an aluminium-6%-magnesium alloy, causes a sharp initial drop in the solidus temperature to a value which remains approximately constant (between 500° and 490° C.) over a composition range of 1·5% magnesium and 5·1% copper. This behaviour is reflected in Fig. 4, in which, at either end of the 6-6 line, there is a sharp initial rise in cracking, with a central portion over which the cracking is roughly constant. In the section at 90% aluminium (Fig. 13 (b)), the first additions of copper to the aluminium-magnesium alloy cause a slight drop in the solidus temperature to about 445° C., followed by a rise to 460° C. at a copper content of about 1%. The first additions of magnesium to the aluminium-copper alloy cause a lowering of the solidus temperature from 548° to 500° C. No appreciable alteration in this temperature is effected by further additions of magnesium up to a magnesium content of approximately 5%; between 5 and 7% magnesium the solidus temperature falls

suddenly to about 460° C. This sudden maximum in the solidus-liquidus temperature interval near the central portion of the 10-10 line, which would account for the bulge in the 3-in. cracking contour in Fig. 4, is not present in Fig. 13 (a), and it would seem that the appearance of this maximum is the cause of the sudden increase in cracking intensity in alloys containing more than 4% copper and 3% magnesium, in which the ratio of magnesium to copper is approximately 2 : 3.

The close agreement between the results of the ring-casting test (Fig. 1 (b)) and the restrained weld-test (Fig. 1 (a)) suggests that the same factors are responsible for cracking above the solidus in both cases, and that the above explanation will apply equally well to the weld-test results. It must, however, be borne in mind when interpreting the cracking results in the light of the appropriate equilibrium or meta-stable-equilibrium diagram, that there may be considerable differences between the degree of equilibrium of the welded or cast alloys and that of the same alloys as indicated by the constitutional diagram.

#### VI.—CONCLUSIONS.

In the aluminium-copper-magnesium system, two types of cracking, namely cracking at temperatures above the solidus and cracking at much lower temperatures, can be distinguished during the cooling to room temperature of welds made in these alloys. The occurrence of low-temperature cracking appears to be dependent on composition, micro-structure, and the degree of restraint imposed on the cooling weld. Sub-solidus cracking may also be initiated by slight cracking occurring at temperatures above the solidus. From the practical aspect, alloys which, because of their composition, are least subject to cracking above the solidus are most subject to sub-solidus cracking under severe stress conditions. Such stresses are unlikely to occur in industrial welding practice, however, and good results should be obtained with alloys containing the minimum amounts of alloying elements to ensure freedom from hot-short cracking.

The range of alloys in which there is pronounced hot-shortness extends up to about 6% copper and 6% magnesium. Alloys outside this range are unlikely to show hot-short cracking in any conditions. A maximum in the susceptibility to cracking occurs in the ternary field at approximately 1·5-2·5% copper and 1-2% magnesium. This finding is in accordance with reported industrial experience. Copper and magnesium have a similar effect on the tendency to cracking, but in general, a combined percentage of copper and magnesium of 12% should ensure negligible cracking.

As with other systems already reported, there appears to be a close relationship between the form of the ternary diagram of cracking and the ternary constitutional diagram.

#### ACKNOWLEDGEMENTS.

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# CRACKING DURING THE CASTING AND WELD-**1128** ING OF THE MORE COMMON BINARY ALUMINIUM ALLOYS.\*

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## SYNOPSIS.

An investigation has been carried out, by means of ring-casting and restrained-weld tests, to determine the tendency for cracking to occur during the casting and welding of the more common binary aluminium alloys. Binary alloys of aluminium with silicon, copper, magnesium, iron, manganese, and zinc have been examined, all the alloys being made from high-purity materials.

The influence of the size of the primary crystals on the cracking tendencies of alloys when cast in ring form has been studied by casting the alloys from three degrees of super-heat, namely 100°, 60°, and 20° C. above the liquidus temperature.

A survey of the macro- and micro-structures of the ring castings has been made and a reasonable degree of correlation established between the structures and the cracking characteristics of the alloys.

In all the systems examined, an initial increase in cracking occurs from the initial addition of the alloying element to super-purity aluminium, followed by a subsequent decrease to zero cracking at some higher percentage of alloying addition. Both the casting and welding characteristics agree in this respect, except in the manganese alloys, which crack to a negligible extent when welded under restraint, and in the zinc alloys, which show no decrease to zero cracking in the restrained-weld tests, whatever the zinc content.

It has been suggested that while the existing theory of cracking at temperatures above the solidus provides an adequate explanation for this behaviour in aluminium binary systems of simple eutectic form, the theory may need considerable amendment when considering alloys of greater constitutional complexity.

## I.—INTRODUCTION.

THE aluminium-silicon system is the only binary system on which any degree of systematic work relating to the cracking that occurs during casting and welding has been carried out. It seemed desirable, therefore, that other binary systems should be examined in order to determine the probable behaviour of the individual binary alloys during casting and welding as a basis for future work on more complex systems, and, at the same time, to determine to what extent their behaviour could

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be correlated with previously-advanced theoretical explanations<sup>1,2</sup> of cracking at temperatures above the solidus.

Alloy series of aluminium with silicon, copper, magnesium, iron, manganese, and zinc have been investigated, all the alloys being prepared from super-purity aluminium and high-purity hardener and so melted and cast as to reduce contamination of the alloys to a minimum.

The ring-casting test,<sup>2</sup> having proved of value for the prediction of the welding properties of a number of binary and ternary aluminium alloy systems, was adopted in the present investigation, and a comprehensive series of ring-casting tests was made. To provide a comparison with the results given by the ring-casting tests, restrained-weld tests were carried out on a smaller number of alloys.

## II.—PREVIOUS WORK.

Little detailed work has been published on the cracking of aluminium binary alloys during casting and welding, and most of the published work, with the exception of that of Singer and Jennings, to which frequent reference will be made in the present paper, has been carried out with alloys of commercial purity.

Verö,<sup>3</sup> Scheuer,<sup>4</sup> and Bochvar and Makimdzhanova<sup>5</sup> made observations of the cracking tendencies of a number of aluminium-silicon alloys. The last-mentioned workers also examined the tendency to cracking of a number of aluminium-copper alloys; in none of these three investigations, however, was work carried out on alloys of low silicon or copper content.

Lees<sup>6</sup> investigated hot tearing in a number of aluminium alloys by means of a casting test, and the few results obtained on a series of aluminium-silicon binary alloys indicated a decrease in the tendency to hot tearing with increasing silicon content. Jolivet and Armand investigated the brittleness of alloys based on commercial-purity aluminium by bending cast bars during cooling from the liquid state. Their work, however, was confined to low alloy contents.

A number of observations has been made on the cracking of aluminium alloys during welding, and there is frequent reference in the literature to the freedom from cracking exhibited by aluminium-manganese alloys. West<sup>8</sup> found that more cracking occurred in welds made in commercial-purity aluminium than in super-purity aluminium under conditions of restraint. Marshall<sup>9</sup> reported that in a series of aluminium-magnesium alloys, weld cracking was most severe in an alloy containing approximately 1% magnesium, but that a considerable

reduction in the amount of cracking occurred when the magnesium content was increased to 3%.

Previous work on the cracking of aluminium binary alloys during casting and welding has thus been mainly concerned with the reduction of cracking in individual alloys; and although a number of restrained-weld tests have been developed, there has been no comprehensive application of a test of this nature to the investigation of cracking.

### III.—EXPERIMENTAL WORK.

In the ring-casting test,<sup>2</sup> the alloy under examination is cast in ring form and caused to solidify under restraint, the total length of cracking appearing on all surfaces of the ring, after complete solidification, being measured. In the restrained-weld test, a weld is made between two sheets of the alloy each 5 in. long, 4 in. wide, and 0·080 in. thick, one end of each sheet being rigidly restrained during welding by means of a jig. The total length of the cracks appearing on both surfaces of the weld is measured after the weld has cooled to room temperature in the restraining jig. In both tests the results are ultimately expressed in the form of curves relating length of cracking with alloy content.

The experimental work consisted in carrying out ring-casting and restrained-weld tests on aluminium-rich alloys in that range of compositions in which pronounced cracking occurred in each of the six binary systems, aluminium-silicon, aluminium-copper, aluminium-magnesium, aluminium-iron, aluminium-manganese, and aluminium-zinc. All the alloys were made from super-purity aluminium and the appropriate high-purity temper alloy or virgin metal. Macroscopic and microscopic examinations were also made of representative ring castings and welds in each of the systems examined.

In the ring-casting tests, each alloy was cast at three different degrees of super-heat, namely 100°, 60°, and 20° C. above the generally accepted liquidus of that particular alloy.

The method of rolling employed for the preparation of sheet for the restrained-weld tests varied slightly for the different alloys, but for the majority of the alloys the material was hot rolled at 430° C. from  $\frac{9}{16}$  in. in thickness, annealed at the rolling temperature, and cold rolled to the final thickness of 0·080 in. An intermediate anneal at a thickness of 0·12 in. was interposed during the cold rolling of the magnesium, zinc, and manganese alloys. In the case of the 10% magnesium alloy, the cast slab, before rolling, was water quenched from 420° C. after 12 hr. soaking at that temperature, and then cold rolled in the quenched state to the final thickness of 0·080 in., with

intermediate anneals at 420° C. followed by water quenching from the annealing temperature. It was hoped by this means to ensure that all rolling was done on the alloy in the  $\alpha$  condition. After rolling, all the sheets were annealed for 1 hr. at 360° C. and slowly cooled from that temperature. All the weld tests were carried out on material in the initially annealed condition.

For the macroscopic and microscopic examination of sections through the ring castings, each specimen was taken by sectioning at a position on the ring one-quarter of the distance round the circumference from the pouring point. The Hume-Rothery cupric chloride macroscopic etching medium was found suitable for the alloys containing silicon, magnesium, and manganese, while for the copper, zinc, and iron alloys the best results were obtained with a hot 10% solution of caustic soda. The etching media used for the microscopic examination of the alloys are indicated on the photomicrographs in Figs. 7-12 (Plates XXIX and XXX).

#### IV.—EXPERIMENTAL RESULTS.

##### 1. Ring Castings.

The results of the ring-casting tests are plotted graphically in Figs. 1-5, and Fig. 6 (Plate XXVIII). For purposes of comparison, an appropriate section of the equilibrium diagram of each system considered has been included in these Figures. The curves indicate the extent to which cracking is affected by alloying additions and by variations in the degree of super-heat prior to casting. It is of interest to note that super-purity aluminium exhibited complete freedom from cracking in the ring-casting test when cast at any of the three degrees of super-heat employed in the present investigation.

A peculiarity of the aluminium-copper system is the second peak of the cracking diagram at approximately 3.5% copper. Certain of the points in this region were checked by the casting of as many as sixteen rings, and the effect would seem to be real. No explanation for this peculiarity can readily be deduced from existing theoretical explanations of cracking at temperatures above the solidus, but possibly it may be due to cracking occurring below the solidus temperature because of weakening of the crystal boundaries through the precipitation of an intermetallic compound in them. If such is the case, the cracking associated with the second peak is not of the type identified as supra solidus cracking in this and previous work, since it will occur below the temperature of complete solidification. The occurrence of such cracking would necessitate a higher stress than that required to produce cracking at temperatures above the solidus; this condition may well arise from

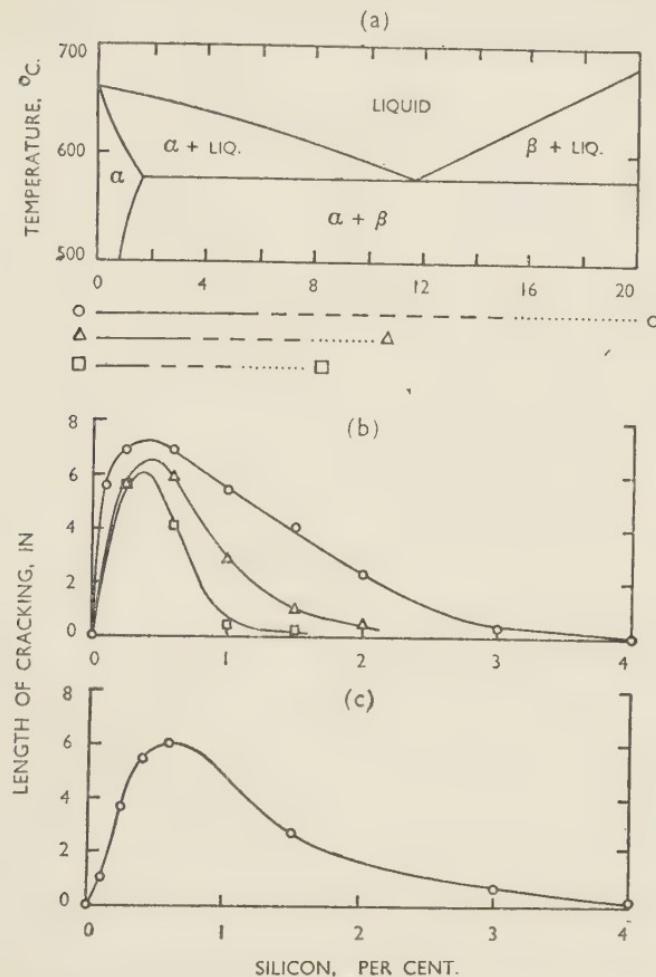


FIG. 1.—Cracking of Ring Castings and Restrained Welds in the Aluminium-Silicon System.

(a) Equilibrium diagram. (b) Cracking of ring castings. (c) Cracking of restrained welds.

KEY TO FIGS. 1-6.

Grain type.

- columnar.
- - - transitional.
- ..... equi-axed.

Casting super-heat.

- 100° C.
- △— 60° C.
- 20° C.

the restraints imposed in the ring-casting test, whereas the required stress would not be attained in a less-severe form of casting or welding test.

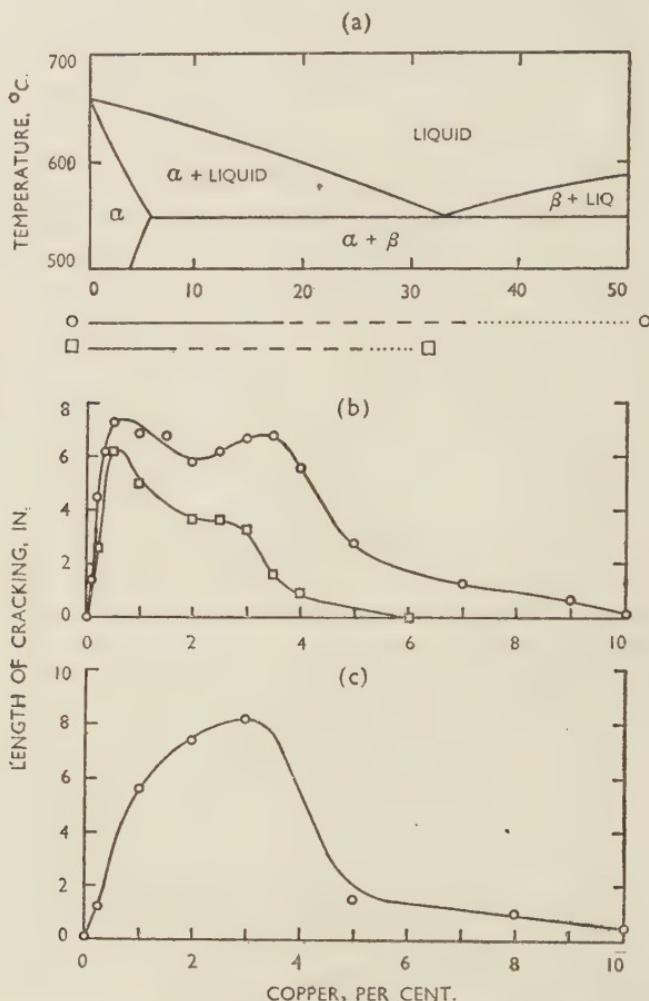


FIG. 2.—Cracking of Ring Castings and Restrained Welds in the Aluminium-Copper System.

(a) Equilibrium diagram. (b) Cracking of ring castings. (c) Cracking of restrained welds.

## 2. Restrained Welds.

The results of the restrained-weld tests are plotted in Figs. 1-5, and Fig. 6 (Plate XXVIII).

In the three alloy systems of aluminium with silicon, copper, and iron, the weld-test results are in close agreement with those of the ring-

casting test. In the aluminium-magnesium system, while the cracking curves obtained in the two tests are of similar form, the precise positions of the maxima are different; in addition, in the restrained-weld tests,

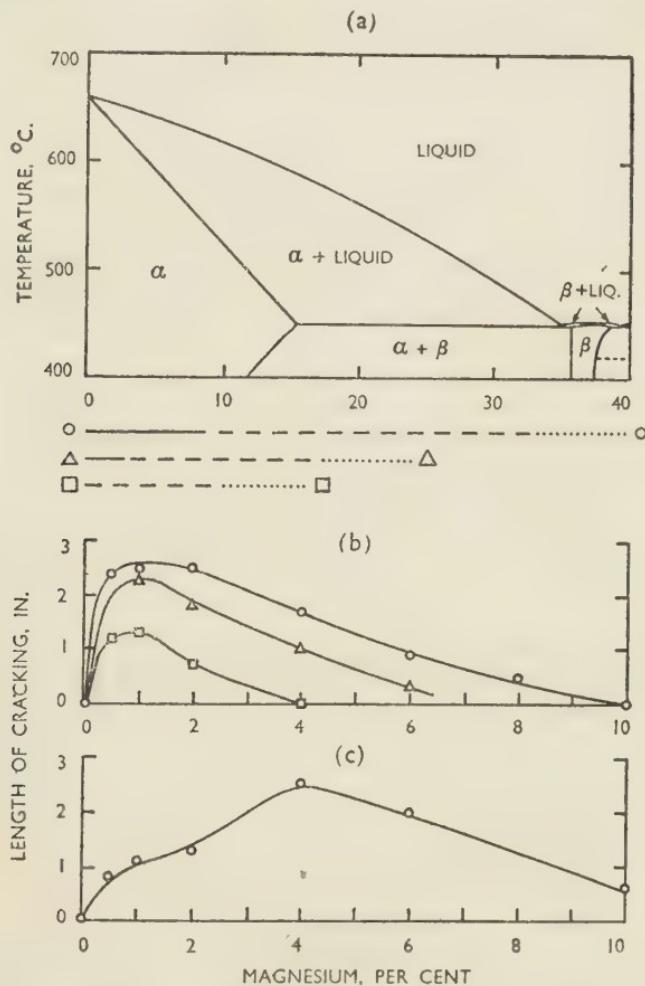


FIG. 3.—Cracking of Ring Castings and Restrained Welds in the Aluminium-Magnesium System.

(a) Equilibrium diagram. (b) Cracking of ring castings. (c) Cracking of restrained welds.

maximum cracking occurs at a higher magnesium content than was observed by Marshall.<sup>9</sup> The reason for this discrepancy is not clear. No double peak was observed on the cracking curve of the copper alloys, possibly for the reason advanced above.

The alloys in the systems of aluminium with manganese and with

zinc do not exhibit the same tendency to cracking in the restrained-weld tests as they do in the ring-casting tests.

The tendency for weld cracking to occur in the aluminium-zinc alloys rises continuously with increasing zinc content; and in the present investigation the most serious cracking was encountered in the

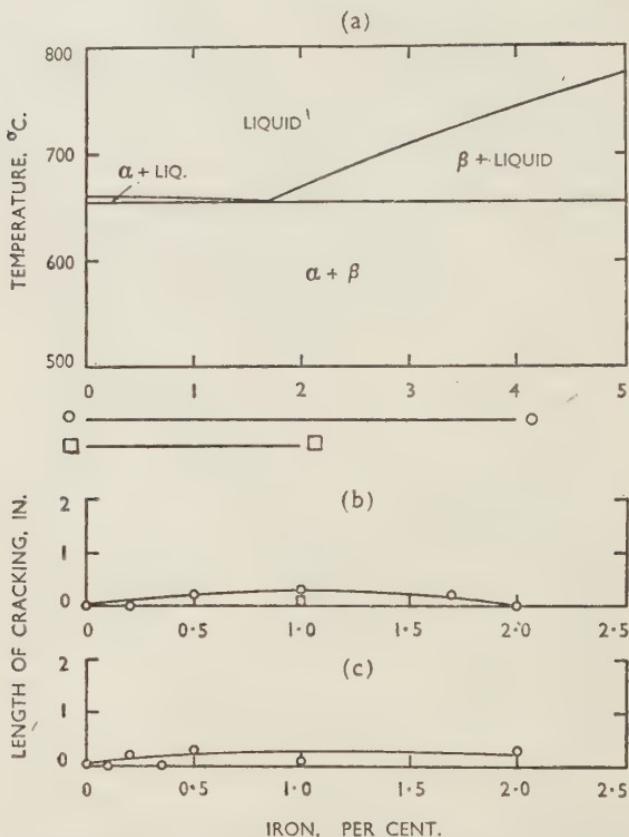


FIG. 4.—Cracking of Ring Castings and Restrained Welds in the Aluminium-Iron System.

(a) Equilibrium diagram. (b) Cracking of ring castings. (c) Cracking of restrained welds.

alloy containing 20% zinc, which was the highest zinc content investigated.

### 3. Macroscopic Examination.

The variation in the size and shape of the primary crystals with increasing alloy content, in all the systems examined by the ring-casting tests, is indicated in Figs. 1-5, and Fig. 6 (Plate XXVIII). In general, when cast in ring form with any particular degree of super-heat,

columnar structure persists in alloys up to a composition just past that which produces the maximum amount of cracking, and a completely equiaxed structure is characteristic of the compositions giving little or no cracking. Alloys between these two extremes of composition possess a transitional structure consisting of a region of columnar crystals at the

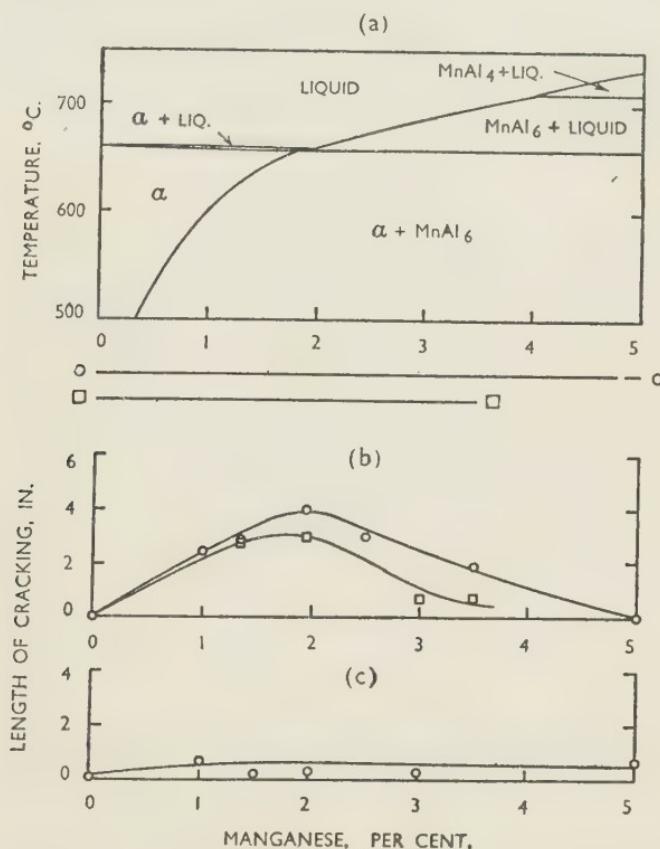


FIG. 5.—Cracking of Ring Castings and Restrained Welds in the Aluminium-Manganese System.

(a) Equilibrium diagram. (b) Cracking of ring castings. (c) Cracking of restrained welds.

outside of the section and a central region in which the crystals are equiaxed. The effect of increasing alloy content on the size and shape of the primary crystals is illustrated for the aluminium-magnesium alloys in Fig. 13 (Plate XXXI); this effect was noted previously by Singer and Fennings.<sup>2</sup> The manganese and iron systems are exceptions to this generalization, for in these alloys a completely columnar structure

persists at the higher alloy contents which give very low values of cracking.

The macrostructures of welds made in alloys in the aluminium-silicon, aluminium-copper, and aluminium-magnesium series were similar to those of the corresponding alloys cast in ring form. As in the ring castings, the alloys of the aluminium-manganese and aluminium-iron series did not show a transition from a columnar to an equi-axed structure with increasing alloy content, but merely a change to a finer columnar structure. In the welds made in the aluminium-zinc alloys, a columnar structure persisted to the highest zinc content investigated (see Fig. 14, Plate XXXI).

#### 4. Microscopic Examination.

The microstructures of the ring castings were surveyed to discover whether any relationship existed between the structures of the alloy and the forms of the curves relating cracking with composition.

In the aluminium-silicon alloys, the first appearance of eutectic was observed in an alloy of silicon content just greater than that producing the maximum cracking with each of the three degrees of superheat investigated, namely in each case in an alloy containing approximately 0.6% silicon. It is evident, therefore, that, after casting, the alloys are considerably out of equilibrium, since the maximum solid solubility of silicon in aluminium under equilibrium conditions is 1.65%. With any one degree of super-heat, the amount of eutectic present in the alloys rises with increasing alloy content, as shown for a casting super-heat of 100° C. in Figs. 7 (a), 7 (b), and 7 (c) (Plate XXIX).

This increase is typical of that encountered in all the systems examined except aluminium-zinc and aluminium-manganese.

It will be noticed that the positions of the maxima in the curves relating composition with cracking are not altered to any appreciable extent by varying the degree of super-heat; hence it would seem that the maximum solid solubility is not altered by the different cooling rates resulting from decreasing the super-heat from 100° to 20° C. To some extent, this is confirmed by the microstructures of a 1% silicon alloy cast at three different degrees of super-heat. Fig. 7 (b) and Figs. 8 (a) and 8 (b) (Plate XXIX) show the structure of the alloy when cast at 100°, 60°, and 20° C., respectively, above the liquidus. The quantity of eutectic present in each section is approximately constant, although the mode of distribution is different.

A depression of the maximum solid solubility from the equilibrium value of 5.7% copper occurs in the ring castings of aluminium-copper

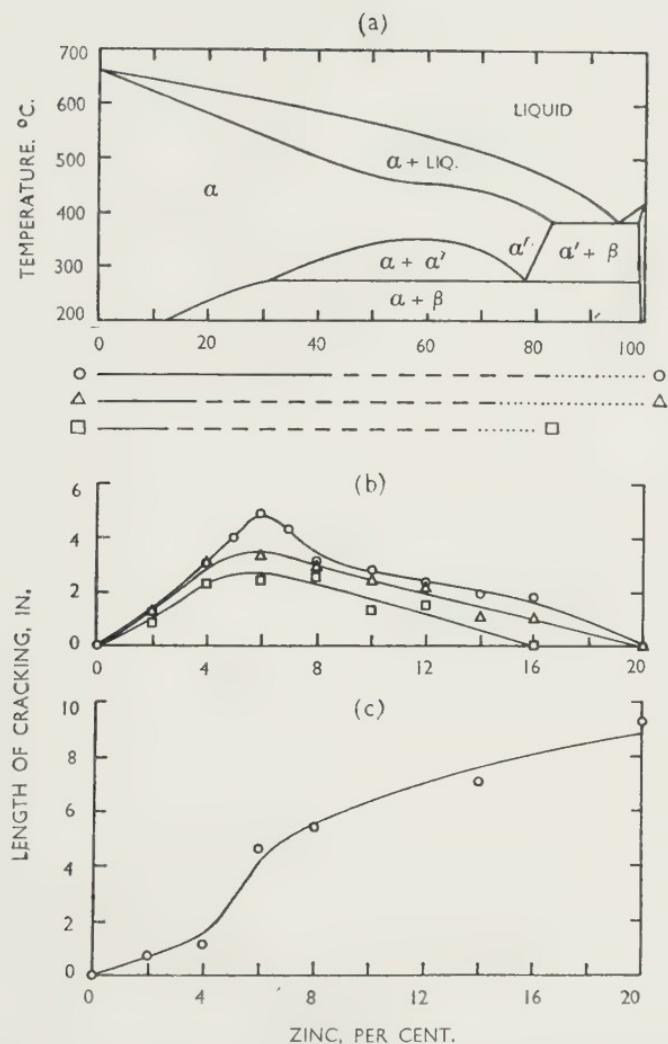
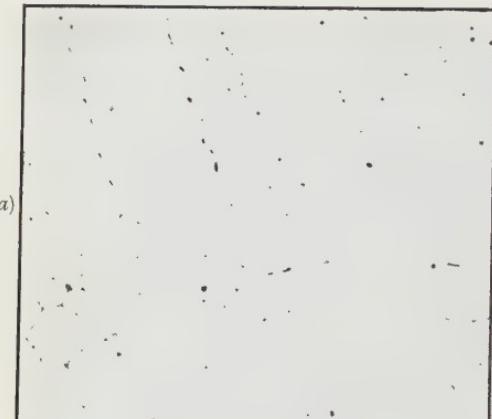


FIG. 6.—Cracking of Ring Castings and Restrained Welds in the Aluminium-Zinc System.

- (a) Equilibrium diagram. (b) Cracking of ring castings.
- (c) Cracking of restrained welds.

7 (a)



7 (b)



7 (c)



FIG. 7 (a).—0·6%-Silicon Alloy Cast at a Super-Heat of 100° C.  $\times 150$ .  
FIG. 7 (b).—1·0%-Silicon Alloy Cast at a Super-Heat of 100° C.  $\times 150$ .  
FIG. 7 (c).—2·0%-Silicon Alloy Cast at a Super-Heat of 100° C.  $\times 150$ .  
FIG. 8 (a).—1·0%-Silicon Alloy Cast at a Super-Heat of 60° C.  $\times 150$ .  
FIG. 8 (b).—1·0%-Silicon Alloy Cast at a Super-Heat of 20° C.  $\times 150$ .  
FIG. 9.—1·7%-Iron Alloy Cast at a Super-Heat of 100° C.  $\times 300$ .

All etched in 0·5% HF.



FIG. 10.—3·5%-Manganese Alloy Cast at a Super-Heat of 100° C. Etched in 5% NaOH.  $\times 150$ .



G. 11.—2%-Manganese Alloy Cast at a Super-Heat of 100° C. Etched in 0·5% HF.  $\times 500$ .

FIG. 12.—20%-Zinc Alloy Cast at a Super-Heat of 100° C. Unetched.  $\times 300$ .

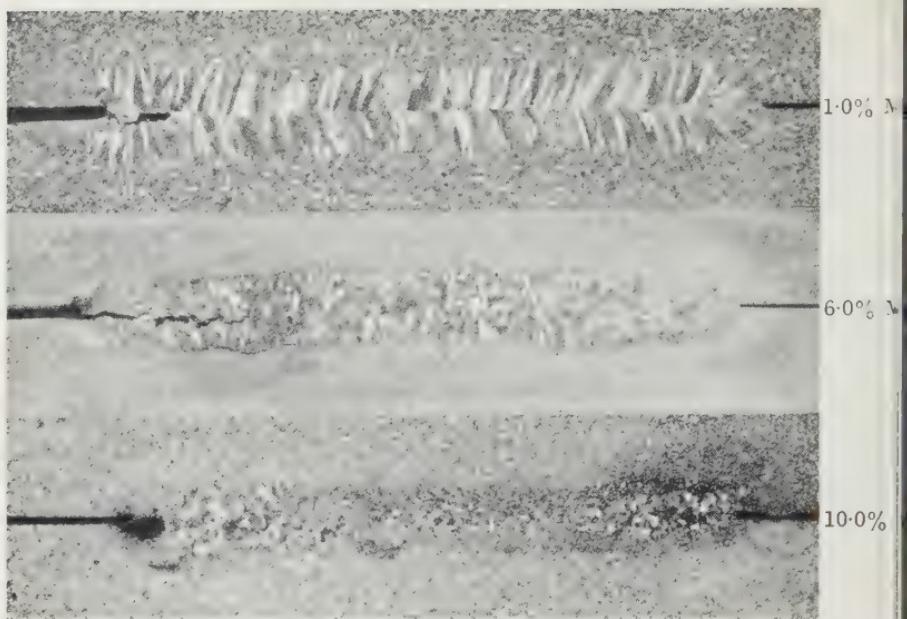


FIG. 13.—Macrostructures of Restrained Welds in Aluminium-Magnesium Alloys.  
Etched in Hume-Rothery's cupric chloride reagent.  $\times 1$ .

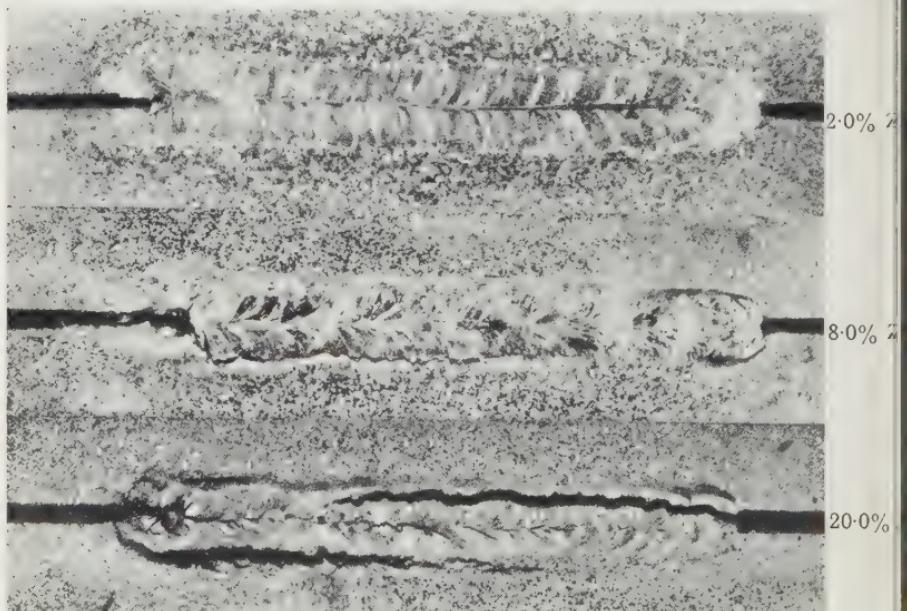


FIG. 14.—Macrostructures of Restrained Welds in Aluminium-Zinc Alloys.  
Etched in 10% NaOH at  $70^\circ\text{C}$ .  $\times 1$ .

alloys. The second phase was first apparent in alloys containing 1% copper in the series cast at the two different degrees of super-heat (100° and 20° C.) examined, such a composition again being just greater than that giving the first maximum on the cracking curves. In the alloys low in copper, the CuAl<sub>2</sub> did not occur in normal eutectic form but had the appearance of small pools of intermetallic compound. It is probable that during the cooling of alloys of low copper content, the  $\alpha$  constituent of the eutectic precipitates preferentially at the eutectic temperature on particles of the  $\alpha$  phase formed in the normal way at higher temperatures, and that the second constituent of the eutectic solidifies in  $\alpha$ -free pools. Eutectic formed in this way, although it does not present the normal eutectic appearance, is not otherwise abnormal since it solidifies at a constant temperature.

On examination under the microscope, the aluminium-magnesium alloys proved to have characteristics similar to those of the copper alloys. The equilibrium solid solubility of magnesium in aluminium was so lowered by the conditions of cooling in the ring-casting test that the second phase was observed in an alloy containing only 4% magnesium. It is probable that Mg<sub>2</sub>Al<sub>3</sub> was in fact present in the 2% magnesium alloy, but in such small quantities and so widely dispersed as to render positive identification impossible. In support of this suggestion, it has been assumed by Lees<sup>6</sup> that 3% can be taken as the maximum solid solubility of magnesium in aluminium in chill-cast alloys.

In the aluminium-magnesium alloys, the  $\beta$  constituent first appeared in pools lacking the characteristic eutectic appearance. In all probability, the reason for this is similar to that advanced for the aluminium-copper alloys. Eutectic of more normal appearance was observed in alloys higher in magnesium.

Iron does not dissolve to any marked extent in aluminium, and, in consequence, eutectic was present in all the iron alloys examined. Under equilibrium conditions, the eutectic alloy in the aluminium-iron system occurs at about 1·7% iron. Under the non-equilibrium conditions maintaining in ring castings, an alloy of this composition contains only about 40% eutectic. The structure of the ring casting of this alloy is shown in Fig. 9 (Plate XXIX). Thus, with aluminium-iron alloys, the effect of rapid cooling is to shift the eutectic alloy to higher percentages of iron. This has already been noted and commented on by Fuss.<sup>10</sup>

As chill cast, aluminium-manganese alloys possess structures which are considerably out of equilibrium. In the ring castings, up to a manganese content as high as 2·5%, the structure was found to consist

almost entirely of solid solution, with small quantities of a second phase ( $MnAl_6$ ) lying among the arms of the dendrites and at the boundaries of the primary crystals. In alloys of higher manganese content, the  $MnAl_6$  was not observed to occur in boundary form but occurred in association with the type of eutectic shown in Fig. 10 (Plate XXX). As suggested by Fuss,<sup>11</sup> it is probable that this eutectic is not entirely of normal form.

The aluminium-zinc alloys up to 20% zinc, the highest zinc content investigated, were found to consist entirely of solid solution.

A microscopic examination was also made of certain of the welded alloys; the results of this examination will be referred to in the appropriate section of the discussion.

#### V.—DISCUSSION.

From the results obtained during the course of the present investigation, it can be postulated that in any alloy in an aluminium binary system of simple eutectiferous form, the amount and distribution of the eutectic is the important factor which determines the extent to which cracking occurs at temperatures above the solidus, either during casting or welding. Other factors, such as the size of the primary crystals, are, by an extension of this hypothesis, of importance as regards supra-solidus cracking only so far as they affect the mode of occurrence of the eutectic and the amount of eutectic necessary to ensure complete healing of boundary fissures.

From the published work of Singer and his colleagues, it is possible to deduce a simple relationship between the amount of eutectic present in an alloy of a binary eutectiferous system and the tendency for cracking to occur in that alloy at temperatures above the solidus. On the basis of previous work by Singer and Cottrell,<sup>1</sup> Singer and Jennings<sup>2</sup> postulated that in a simple binary system the amount of cracking occurring at temperatures above the solidus reaches a maximum in the alloy having the greatest temperature interval between solidus and liquidus, that is, in the alloy of composition corresponding to the maximum solid solubility of alloying element. Hence, in such systems, those alloys at the maxima of the curves relating cracking with composition should be the alloys of composition corresponding to the maximum solid solubility on the constitutional diagram considered, whether metastable or equilibrium depending on the conditions under which the cracking is determined. In alloys of higher alloy content, increasing amounts of eutectic should be discernible; the first reduction in severity of cracking should coincide with the first appearance of eutectic, and further reduction in

the severity of cracking should be accompanied by an increase in the amount of eutectic present. The present examination of ring castings in the three simple binary systems, aluminium-silicon, aluminium-copper, and aluminium-magnesium, has confirmed this deduction.

It was, however, suggested by Singer and his co-workers that the decrease in the amount of cracking obtained in the aluminium-silicon series by increasing the silicon content beyond the amount corresponding to the maximum on the cracking curve, while a function of the increasing amount of eutectic present, was also related to the attendant change in the size and shape of the primary crystals from coarse columnar to fine equi-axed. It would now seem that in aluminium binary systems of simple form, the size of the crystals is only of importance so far as it affects the mode of eutectic distribution. Thus, for example, in the case of a 1% silicon alloy cast at three degrees of super-heat, 100°, 60°, and 20° C., both the intensity of cracking and the crystal size diminish with decreasing super-heat, although the amount of eutectic present in the structure remains roughly constant. The amount of eutectic present in the crystal boundaries, however, increases with decrease in super-heat. When the eutectic is present at the crystal boundaries it has the maximum effect in permitting free movement of the crystals to accommodate casting and thermal contraction, and in "healing" the voids caused by such crystal movement and, consequently, in reducing the tendency to cracking. The finer the size of the primary crystals, the greater is the probability of the eutectic being present at their boundaries. Again, with a fine crystal size, the thermal contraction is more likely to be accommodated by a slight general movement of the crystals, with smaller boundary dislocations than in an alloy in which the primary crystals are large, and hence the smaller the amount of eutectic necessary for healing the voids so caused. The two effects, crystal size and eutectic distribution, are, however, very closely related.

The results of the restrained-weld tests on the three binary systems, aluminium-silicon, aluminium-copper, and aluminium-magnesium, plotted in Figs. 1 (c), 2 (c), and 3 (c), are in fair agreement with the results of the ring-casting tests, plotted in Figs. 1 (b), 2 (b), and 3 (b). The similarity between the results of the two tests suggests that the same factors are responsible for cracking in each case, and that the results obtained in the restrained-weld tests can be explained in the same way as those obtained in the ring-casting tests.

In the aluminium-iron alloys, the small temperature interval between liquidus and solidus would suggest, on the basis of the theoretical reasoning of Singer and Jennings,<sup>2</sup> that the hot-short temperature

range is negligibly small; and in consequence very little cracking should be encountered in the ring-casting test, as was in fact found to be the case (Fig. 4 (b)). In all the aluminium-iron alloy ring castings that were examined, a completely columnar structure was observed. Eutectic was present in all the alloys, a finding in accordance with the suggestion that the presence of eutectic in the structure has a greater effect in reducing cracking than a reduction in the size of the primary crystals. Eutectic was present in the alloys in smaller quantities than would be expected from equilibrium considerations; and, in the conditions of the ring-casting test, an amount of eutectic sufficient to ensure complete freedom from cracking was only obtained in an alloy beyond the equilibrium eutectic composition. The results obtained in the restrained-weld tests with aluminium-iron alloys are in close agreement with the results given by the ring-casting tests.

When the eutectic present in the alloy does not occur in the normal manner, other factors become of greater importance as regards cracking. Examples of such alloys are encountered in the aluminium-manganese system. According to Dix, Fink, and Willey,<sup>12</sup> the temperature interval between solidus and liquidus in alloys containing less than about 2% manganese is less than 2° C. Thus, on the basis of the existing explanation of cracking at temperatures above the solidus, no serious cracking would be expected in such alloys, a prediction which was confirmed by experiment in the case of the aluminium-iron alloys. In actual fact, a considerable amount of cracking was observed in ring castings in the aluminium-manganese system (Fig. 5 (b)). It is probable that in alloys containing 2·5% manganese or less, the presence of MnAl<sub>6</sub> in the crystal boundaries promotes boundary weakness, so causing cracking under the severe conditions of restraint imposed by the ring-casting test. Cracking at the crystal boundaries in the 2% manganese alloy was in fact found in conjunction with MnAl<sub>6</sub> in boundary form, as is illustrated in Fig. 11 (Plate XXX).

In alloys of higher manganese content, the MnAl<sub>6</sub> does not occur in boundary form, but is found in association with the type of eutectic shown in Fig. 10 (Plate XXX), so that cracking, when it occurs, can be healed in the manner previously envisaged by Singer and Jennings.<sup>2</sup> Little or no cracking was observed in restrained-weld tests carried out on aluminium-manganese alloys containing up to 5% manganese, and it is of interest to consider reasons for the difference in the results given by the two types of test.

Cracking at temperatures above the solidus can occur when the degree of restraint imposed on the solidifying mass is very small. Cracking of manganese alloys in which MnAl<sub>6</sub> is present at the crystal

boundaries, though probably occurring mainly at temperatures below the solidus, may sometimes be initiated by the stress-raising effect of small cracks produced at temperatures above the solidus, since the fractures in cast rings of such alloys often present a duplex appearance, consisting of a shiny portion characteristic of fractures occurring above the solidus, and a matte portion characteristic of fractures produced at much lower temperatures. For such a fracture to occur, a certain minimum stress is necessary. At temperatures below the solidus, there is, in the ring-casting test, an effective length of about 7 in. of metal contracting across a sectional area of approximately 0.30 in.<sup>2</sup> At sub-solidus temperatures, the stresses across this area are therefore likely to be high. On the other hand, in the restrained-weld test, the effective length of metal cooling from the solidus temperature is about 0.5 in. (the width of the weld), contracting across a sectional area of about 0.24 in.<sup>2</sup> (Since, in a ductile alloy, contraction of the bulk of the sheet can be accommodated by elongation, it is not likely to increase the resulting stress greatly.) With ductile alloys the stresses imposed at sub-solidus temperatures on the metal in the restrained-weld test will therefore be much smaller than in the ring-casting test, and it is probable that while the stresses in the ring-casting test are sufficient to cause fracture, the stresses set up in welding are not. This suggestion provides an explanation for the difference between the results of the ring-casting and the restrained-weld tests in aluminium-manganese alloys in which MnAl<sub>6</sub> is present at the crystal boundaries. In alloys of higher manganese content, as has already been mentioned, any cracking which occurs is of the normal supra-solidus type. The suggestion also provides an explanation for the fact that, under industrial conditions of welding, aluminium-manganese alloys are regarded as free from any tendency to cracking. In support of the above hypothesis, boundary MnAl<sub>6</sub> similar to that observed in the section from the ring casting was found in a section through the weld made in the test plate of the 2% manganese alloy.

In the complete absence of eutectic, as in certain alloys in the aluminium-zinc system, factors other than those operative in the case of aluminium-manganese alloys may be of importance. In the aluminium-zinc system, the alloys up to 20% zinc were found to consist entirely of solid solution. No ready explanation for the increase and decrease of cracking in the ring-casting test with increasing zinc content is provided by the theory of Singer and Jennings, on the basis of which considerable cracking would be expected in the alloy containing 20% zinc. Small, intercrystalline cavities were observed, however, in a polished unetched section through a ring casting of the 20% zinc alloy

(see Fig. 12, Plate XXX), and it is possible that in the zinc alloys solidification contraction, in the absence of any healing eutectic, is accommodated by movement of the primary crystals, one upon the other. This movement will occur less easily, and will be accompanied by the formation of more boundary cracking, in the alloys of large crystal size (less than 8% zinc; see Fig. 6 (b), Plate XXVIII) than in the alloys of higher zinc content, in which the crystals are finer and of a more equiaxed form. Because of the absence of healing eutectic, these cracks, if large, are likely to lead to fracture of the ring under the conditions of restraint imposed during the casting test. The finer the cracks, the less is the likelihood of fracture; and, in fact, no major fracture of a cast ring was observed with the alloy containing the fine voids shown in Fig. 12 (Plate XXX). Similar views have been expressed in more general terms by Lees<sup>6</sup> and Marshall.<sup>9</sup>

This suggestion appears to provide an explanation of the experimental results obtained from the aluminium-zinc ring castings. The restrained welds made on the zinc alloys showed no decrease in cracking up to a zinc content as high as 20%. On the basis of the above-mentioned reasoning, it would therefore be expected that in these alloys the primary crystals would be of columnar form throughout the range of compositions examined. This was found to be so, and none of the welds examined in the aluminium-zinc system up to a zinc content of 20% exhibited any indication of a fine equiaxed crystal structure (compare Fig. 13 (Plate XXXI) for the magnesium alloy with Fig. 14 (Plate XXXI) for the zinc alloys).

#### VI.—CONCLUSIONS.

(1) The six binary aluminium alloy systems examined show the characteristic relation between cracking tendency and alloy content, namely an increase in the amount of cracking with the initial addition of the alloying element to super-purity aluminium, followed by a decrease to zero cracking at some higher percentage of alloying addition. Both the welding and casting characteristics agree in this respect, with the exceptions of (a) the iron alloys, which show very little tendency to cracking in either the ring-casting or the restrained-weld tests, (b) the manganese alloys, which crack to a negligible extent when welded under restraint, and (c) the zinc alloys, which, in the restrained-weld tests, show no decrease to zero cracking at high zinc contents.

(2) It has been established that, in a number of the systems, the first reduction in the severity of cracking beyond the maximum on the characteristic cracking curve is accompanied by the first appearance of

eutectic in the alloy, in accordance with the theory of Singer and Jennings. This theory provides an adequate explanation for cracking at temperatures above the solidus in aluminium binary systems of simple eutectiferous form (aluminium-silicon, aluminium-copper, aluminium-magnesium, aluminium-iron).

(3) The simple theory does not provide an explanation for the cracking in alloys of greater constitutional complexity (aluminium-zinc, aluminium-manganese), and explanations based on the structures of these alloys have been advanced.

(4) It would seem that the amount of eutectic in an alloy, and the way in which it is distributed, are the most important factors in determining the extent to which cracking occurs at temperatures above the solidus, and that other factors, such as the size of the primary crystals, are only of importance so far as they affect the mode of occurrence of the eutectic and the amount of eutectic necessary to provide complete healing of boundary fissures. In the absence of eutectic, or when the eutectic present is not normal in type, other factors become of greater importance. In the presence of a brittle constituent around the primary crystals, cracking can occur at temperatures below the solidus when the stresses applied to the cooling metal are of a sufficient order of magnitude.

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